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FROM

THE PHYSICAL LABORATORY

PROFESSOR GEORGE WALTER STEWART, EDITOR

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Die Wirkung einer Verletzung durch Abschaben auf die elektrische Leitfähigkeit des Selens.

(The Effect of Rupture by Abrasion on the Electrical Conductivity of Selenium.)

Von F. C. Brown.

Als ich vor einiger Zeit die Oberfläche des Selens einer Giltayzelle abfeilte, um direkt gewisse Grenzen für die Tiefe des Eindringens von Licht in das Selen zu ermitteln¹⁾), entdeckte ich einen neuen Effekt.

Dieser Effekt mechanischer Verletzung auf positiv-lichtempfindliches Selen ähnelt im allgemeinen den vielen anderen bekannten Effekten an diesen Varietäten des Selens. Die Verletzung verursacht eine Zunahme der Leitfähigkeit, aber diese Zunahme ist keine bleibende. Die Erholung erfolgt äußerst langsam und erfordert oft mehr als einen Monat, bis das Selen den vor der Verletzung bestehenden elektrischen Zustand erreicht. Die Versuche sind besonders interessant wegen ihrer Beziehung zur Theorie des dynamischen Gleichgewichtes lichtempfindlichen Selens²⁾). Die drei Komponenten des Selens sind im dynamischen Gleichgewicht in einer Art fester Lösung vorhanden. Aber das Gleichgewicht muß notwendig in gewissen Gebieten oder Konfigurationen wirksam sein. Die Verletzung der Oberfläche des Selens stört notwendig diese Konfiguration und infolgedessen die Gleichgewichtsbedingung. Die Wiederherstellung der Gleichgewichtsbedingung erinnert an das Wiederwachsen von Kristallen, wie es bekanntlich unter besonderen Bedingungen eintritt, wenn man gewisse große Kristalle zertrümmert oder zerbrochen hat.

Die erwähnte Verletzung habe ich durch Feilen hervorgebracht und Giltay durch einen Sandstrahl. Ich verfuhr in der Weise, daß ich die Oberfläche des Selens zwischen den Drähten einer Giltayschen Zelle gleichmäßig abfeilte. Das Selen, das fortgefeilt worden war, wurde im allgemeinen gewogen, um die Beziehung zwischen der Leitfähigkeit und der Selenmenge zu ermitteln, sowie ferner, um die Wirkung fortgesetzten Feilens festzustellen.

1) Phys. Rev. **34**, 201, 1912.

2) Phys. Rev. **33**, 403, 1911.

Das Hervorbringen der Verletzung.

Ich werde zunächst das Verfahren zum Hervorbringen der Verletzung beschreiben, das mir Herr J. W. Giltay brieflich mitzuteilen die Freundlichkeit hatte. Seinen Bericht erhielt ich erst ein paar Tage, nachdem ich meine Vorversuche über den Gegenstand beendet hatte, und wenn er auch das Datum seiner Versuche nicht angibt, so ist es doch durchaus möglich, daß er die Erscheinung zuerst entdeckt hat.

Herr Giltay erzeugte die Verletzung durch einen sanften Sandstrahl. Der von ihm benutzte Apparat ist in Fig. 1 darge-

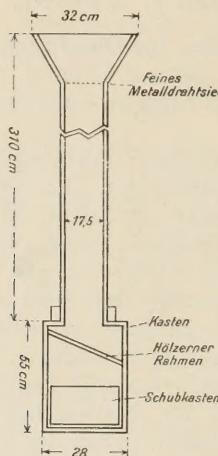


Fig. 1.

stellt und soll im folgenden mit seinen eigenen Worten beschrieben werden: „Der Apparat, in dem der Sand fällt, besteht aus einem quadratischen Holzrohr, das oben in einem konischen Stück und unten in einem Kasten endet. In diesem Kasten ist in geneigter Lage ein hölzerner Rahmen angeordnet, wie es die Figur zeigt. Dieser Rahmen trägt ein Drahtnetz, auf das der mit dem Sandstrahl zu behandelnde Gegenstand gelegt wird. In den Kasten ist ferner ein hölzerner Schubkasten eingesetzt, von dem zwei Exemplare erforderlich sind. Einer dieser Schubkästen wird mit Sand gefüllt, und der Sand fällt in den anderen, der in dem Kasten steht. Dann wird der volle Schubkasten herausgezogen und durch den anderen ersetzt, und dieses Spiel wiederholt sich so oft, wie nötig“. In dem Giltayschen Apparat wird die Ver-

letzung durch den auf die Oberfläche des Selens fallenden Sand hervorgebracht.

Mein Verfahren, die Verletzung herbeizuführen, bestand in der Anwendung einer feinen Schlichtfeile, die so gehauen war, daß sie das Selen zwischen den Drähten entfernte, die Drähte aber nicht angriff. Es ist schwer, genau zu sagen, worin der Unterschied zwischen der durch die Feile und der durch den Sandstrahl hervorgerufenen Verletzung bestehen wird. Vielleicht dürfte die Feile in ihrer Wirkung größer sein. Soweit jedoch die Tatsachen gehen, zeigt sich keine Andeutung irgendwelcher Verschiedenheit in der Verletzung, einerlei, nach welchem Verfahren sie herbeigeführt worden ist. Wenn dies sich so verhält, so hat das Feilverfahren den Vorteil, daß man die beseitigte Selenmenge bestimmen kann.

Der Effekt der Verletzung.

Die Entdeckung dieses neuen Effektes erfolgte ganz zufällig. Ich benutzte eine Feile, um die Oberflächenschicht des Selens einer Giltayschen Zelle zu entfernen, in der Absicht, herauszufinden, ob das gesamte Selen der Zelle leitend sei, sowie auch in der Hoffnung, die Lichtempfindlichkeit, d. h. das Verhältnis der Leitfähigkeit im Licht zu jener im Dunkeln, zu steigern. Der erste Versuch zeigte, daß die Leitfähigkeit zunahm, wenn das Selen abgefeilt wurde. Bei dem zweiten Versuch wurde das Selen, etwa 0,06 g, zwischen acht parallelen Drähten der Giltayschen Zelle betrachtet. Die Leitfähigkeit im Dunkeln betrug 87 Skalenteile. Nach Abfeilen einer ganz geringen Menge Selen von der ganzen Oberfläche stieg die Leitfähigkeit tatsächlich auf das Fünffache. Mehr als die Hälfte des Selens wurde entfernt, ehe die Leitfähigkeit im Dunkeln bis auf 150 Skalenteile sank. Als der Prozeß fortgesetzt wurde, bis nur noch eine dünne Selenschicht übrig blieb, sank die Leitfähigkeit nach 24 Stunden im Dunkeln auf 20 Skalenteile. Die Lichtempfindlichkeit betrug dann 66:1 bei einer Probe, die vor der Verletzung der Oberfläche ungefähr 30:1 ergeben hatte. Die Leitfähigkeit im Licht wie im Dunkeln wurde durch das Feilen zunächst gesteigert. Dies deutet auf eine Veränderung in den Eigenschaften des Selens infolge der Einwirkung hin.

Giltay hat seine Entdeckung auch ganz zufällig gemacht. Er erzählt: „Ich hatte zwei Zellen, die beide eine etwas bläuliche Farbe zeigten, wie dies bei meinen Zellen zuweilen vorkommt... Der Dunkelwiderstand betrug

bei Nr. 31 b: $R = 190000$ Ohm, und in diffusem Licht: $R/22,5$;
bei Nr. 32 b: $R = 300000$ Ohm, und in diffusem Licht: $R/25$.

Da die Zellen nicht gut aussehen, wenn sie blau sind, so behandelte ich Nr. 31 b mit dem Sandstrahl (siehe Fig. 1), um die gewöhnliche Farbe der Selenoberfläche zu erhalten. Ich erwartete, daß der Widerstand und ebenso die Empfindlichkeit etwas größer werden würden, weil die Selenschicht etwas dünner wurde. Beide Zellen wurden nach der Behandlung mit dem Sandstrahl in den Dunkelkasten gebracht und tags darauf beide abermals gemessen. Dabei ergab sich:

Nr. 31 b: $R = 70000$ Ohm, und in diffusem Licht: $R/8,2$;

Nr. 32 b: $R = 300000$ Ohm, und in diffusem Licht: $R/25$.

Nach 15 Tagen wurden die Zellen wieder gemessen. Die Zimmertemperatur . . . war viel niedriger . . . Die Zellen lieferten jetzt:

Nr. 31 b: $R = 140000$ Ohm, und in diffusem Licht: $R/25$;

Nr. 32 b: $R = 430000$ Ohm, und in diffusem Licht: $R/44$.

Dies scheint zu beweisen, daß der Dunkelwiderstand durch den Sandstrahl verringert, sowie daß die Empfindlichkeit in derselben Weise wie durch Erhitzen der Zelle verringert worden ist . . . Ich muß jedoch hinzufügen, daß ich diesen Versuch wegen Zeitmangels nur einmal gemacht habe . . .“

Es mag hier bemerkt werden, daß bei Zelle 31 b der Widerstand nach dem Zeitraum von 15 Tagen um 100 v. H. stieg, während der Widerstand von Zelle 32 b in derselben Zeit nur um 43 v. H. zunahm. Wahrscheinlich rührte die Größe der Widerstandszunahme beider Zellen um den letztgenannten Betrag von einer Temperaturänderung her, aber die weitere Zunahme war zweifellos einfach eine Erholung der Wirkung des Sandstrahles.

Die langsame Änderung nach der Verletzung.

Nachdem ich bemerkt hatte, daß das Selen bei den Versuchen Giltays sich anscheinend von der Wirkung des Sandstrahles erholte, suchte ich nach einer Erholung von der Wirkung des Feilens. Die Leitfähigkeit nahm bei den verschiedenen Versuchen, die ich machte, sehr langsam ab. Die nachstehende Tabelle liefert ein Beispiel aus einer Beobachtungsreihe.

Der hervortretendste Umstand, der aus der Betrachtung der Tabelle hervorgeht, ist, daß das Feilen die elektrischen Eigenschaften des Selens verändert hat. Nach der ersten Beseitigung von Selen durch die Feile nahm die Leitfähigkeit dadurch von 2,5 auf 18,0 zu und die Leitfähigkeit im Licht von 86 auf 215. Die Behandlung erfolgte jedoch im diffusen Zimmerlicht, und infolgedessen muß ein kleiner Teil der gesteigerten Leitfähigkeit als Folge unvollkommener Erholung vom Licht erklärt werden. Die gesteigerte Leitfähigkeit im Licht kann aber nicht anders erklärt werden als auf Grund veränderter Eigenschaften des Selens. Die

Nummer der Behandlung mit der Feile	Abgefeilte Menge Selen	Zeit der Beseitigung	Leitfähigkeit		Empfindlichkeit im Licht
			im Dunkeln	vor den Abfeilen, bei 25° C	
1	0,0022 g	13. Jan.	9 ^h 25'	a. m.	2,5
			9 ^h 30'		18
			9 ^h 45'		15
			12 ^h 00'		14,4
			3 ^h 00'	p. m.	13
			5 ^h 00'		12
			12 ^h 00'		8,6
					7,4
		14. Jan.			6,5
		15. Jan.			6,3
2	0,0098 g	17. Jan.			6,0
		18. Jan.			
		23. Jan.			
		24. Jan.	10 ^h 40'		
			11 ^h 00'		
		25. Jan.		3,0	
		26. Jan.		2,5	
		29. Jan.		1,8	
		30. Jan.		1,7	
		11. Febr.		1,4	
3	0,011 g	16. Febr.	8 ^h 00'		1,3
			8 ^h 05'		1,4
			10 ^h 30'		1,1
			3 ^h 00'	p. m.	0,75
					0,5
		17. Febr.			0,45
		20. Febr.			0,2
		11. März			0,16
		3. April			0,14
		29. April			

18/1

215

bei 23° C

" 22° C

" 22° C

" 22° C

" 21° C

53

bei 20° C

" 21° C

" 19° C

" 22° C

49

38/1

24/1

bei 26° C

" 24,5° C

" 24° C

8,8

44/1

48/1

56/1

7,9

7,8

Größe der Leitfähigkeitszunahme scheint nach dem ersten Feilen abzunehmen.

In allen Fällen zeigt sich offenbar eine langsame Abnahme der Leitfähigkeit nach dem Feilen, die viel langsamer ist als irgend eine Veränderung des Selens infolge irgendwelcher anderer bekannter Agenzien. Nach dem dritten Feilen an der betrachteten Probe änderte sich die Leitfähigkeit noch nach einem Zeitraum von mehr als zwei Monaten. Es ist indessen nicht ganz klar, ob die gesamte Änderung ihrer Natur nach einer Erholung auf den vor Beginn des Feilprozesses herrschenden Zustand ist. Vermutlich waren an der Probe der Zelle 0,06 g Selen. Nachdem ich hier von etwas mehr als ein Drittel entfernt hatte und Gleichgewicht abgewartet hatte, betrug das Leitvermögen 0,14, oder nur ein Zwanzigstel ihres Betrages vor dem Abfeilen. Danach hat es den Anschein, daß ein großer Teil der Änderung keine Erholung war. Eine andere Beobachtungsreihe an einer anderen Selenprobe stellen die Kurven in Fig. 2 dar. Durch die dritte Befilung, die am fünften Tage stattfand, wurde weniger als die Hälfte des Selens entfernt, und doch sank schließlich die Leitfähigkeit von 7 auf 1,7. Möglicherweise wird nicht nur das fortgeschaffte, sondern auch das nahe an der Oberfläche befindliche Selen unfähig gemacht, zu leiten. Bekanntlich¹⁾ wird das lichtempfindliche Selen durch Pulvern in die nichtleitende amorphe Form übergeführt. Die Oberfläche der Zelle zeigt nach dem Feilen ein schwarzes, glänzendes Aussehen, wie das glasige Selen. Es schien mir jedoch, als ob sich im Laufe eines Monats die Oberflächenfarbe in das gewöhnliche Grau verwandelte.

Die Natur des Effektes im Vergleich mit anderen Effekten.

Die einzigen anderen Effekte, die mit dem hier beschriebenen verwandt sein könnten, sind vielleicht die Wirkungen des Druckes und des Radiums. Druck vermindert den Widerstand in sehr bemerkenswertem Maße²⁾, aber der Effekt zeigt geringe oder gar keine Hysterese. Der Widerstand kehrt sehr rasch auf seinen ursprünglichen Wert zurück. Ich kenne tatsächlich keinen anderen Effekt, von dem die Erholung so rasch vor sich geht. Später hat jedoch Montén beobachtet, daß bei Drucken von der Größe von 30 000 Atmosphären eine geringe Hysteresewirkung vorhanden war. Dieser Unterschied zwischen dem Druckeffekt und dem Verletzungseffekt ist vermutlich der, der im Namen liegt. Die

1) A. P. Saunders, *Journ. Phys. Chem.* **4**, 423.

2) Brown and Stebbins, *Phys. Rev.* **26**, 273, 1908; Montén, *Arkiv för Math., Astr. och Fysik* **4**, 1, 1908.

angewandten hydraulischen Drucke waren gleichförmig auf der Oberfläche und beanspruchten somit keinen Teil des Selens über die Elastizitätsgrenze hinaus, während durch Behandlung mit der Feile oder mit dem Sandstrahl Teile des Selens tatsächlich abge-

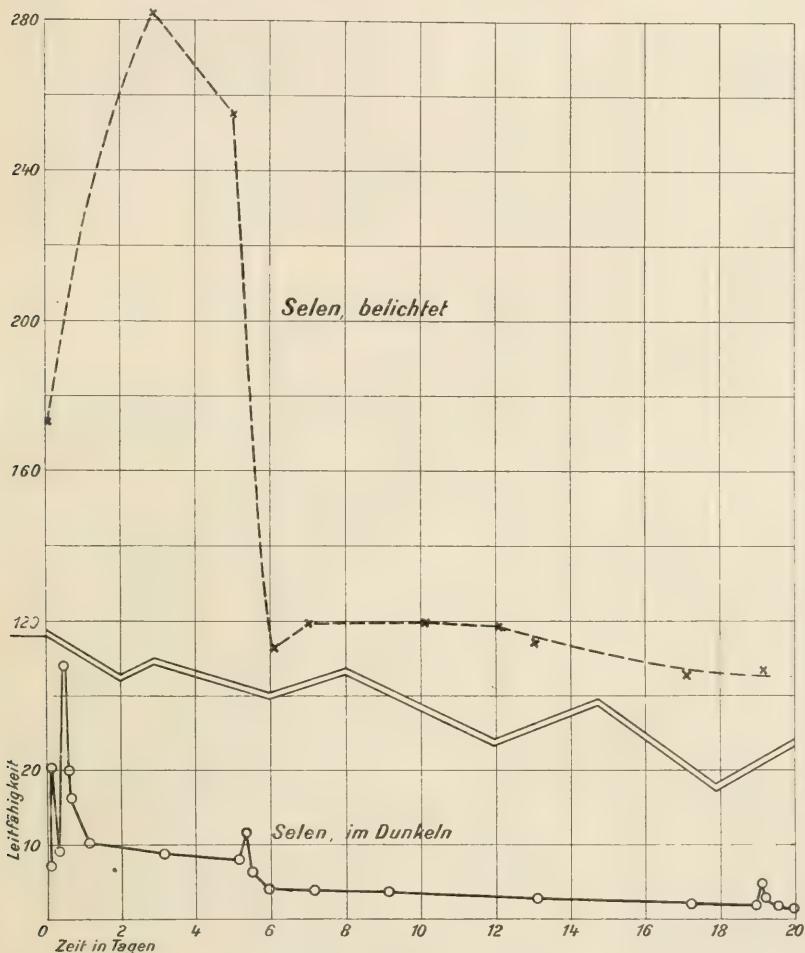


Fig. 2.

brochen wurden und vielleicht ein großer Teil der Oberfläche über die Elastizitätsgrenze beansprucht wurde.

Man könnte erwarten, daß die α -Strahlen des Radiums einen Effekt von der Art jenes durch Verletzung mittels Abschabens

hervorbrachten. In der Arbeit von Brown und Stebbins¹⁾ sind die Ergebnisse kurzer Expositionen gegen Radium mit der Aktivität von 2000000 beschrieben. Die Widerstandsabnahme war von derselben Größenordnung, wie die durch Abschaben herbeigeführte. Auch die Erholung erfolgt langsamer als von der Exposition gegen Licht, aber nicht so langsam als wie von der Feilebehandlung. Es ist daher sehr wohl möglich, daß der Radiumeffekt ein Verletzungseffekt ist. Eine Untersuchung langer Expositionen von Selen gegen Radium, vielleicht solcher von vielen Tagen, würde weitere Aufschlüsse hierüber geben. Zweifellos würde der Widerstand dauernd abnehmen, bis das Radium entfernt würde, statt in ein paar Minuten einen Gleichgewichtszustand zu erreichen, wie bei Exposition gegen Licht von entsprechender Intensität der Fall ist.

Der Effekt des Abschabens auf negativ lichtempfindliches Selen²⁾.

Der Umstand, daß negativ lichtempfindliches Selen instabil ist, und daß sein Widerstand durch einfaches Schütteln zunimmt, würde zu der Vermutung führen, daß Verletzung durch Abschaben eine ähnliche Zunahme herbeiführen würde, und nicht die an positiv lichtempfindlichem Selen erzeugte Abnahme.

Die Einheit negativ lichtempfindlichen Selens, die ich untersucht habe, hatte einen Widerstand von ungefähr 19,2 Ohm im Dunkeln bei 0,14 Volt Klemmenspannung, und 20,7 Ohm bei Exposition gegen das diffuse Zimmerlicht. Nachdem mit einer Feile über ein Viertel der Selenoberfläche gestrichen worden war, stieg der Widerstand auf 26,2 Ohm, und nachdem die Feile einfach über das zweite Viertel gezogen worden war, stieg er weiter auf 28 Ohm, und eine weitere ähnliche Behandlung des dritten Viertels ließ den Widerstand auf 36,9 Ohm ansteigen. Da ich nicht gern Gefahr laufen wollte, die Probe unnötig zu verderben, führte ich die Behandlung nicht weiter durch. Nach einem Aufenthalt von einer Woche im Dunkeln hatte sich der Widerstand nur auf 34 Ohm im Dunkeln erholt. Nach Verlauf von zwei Monaten hatte sich die Leitfähigkeit auf 20,7 Ohm im Dunkeln und 21,8 Ohm im Licht des Zimmers erholt. Es ist noch zu bemerken, daß die Erholung fast vollkommen war, sowie auch, daß der Prozeß gerade so langsam verlief wie die Erholung beim positiv lichtempfindlichen Selen. Es ist interessant und wichtig, daß die Schabeeffekte an positiv lichtempfindlichem und an negativ licht-

1) a. a. O.

2) F. C. Brown, diese Zeitschr. 11, 482, 1910; Lilah B. Crum, On Some Characteristics of Light Negative Selenium. Phys. Rev. 33, 538, 1911.

empfindlichem Selen entgegengesetztes Vorzeichen haben, und ferner, daß die Effekte im übrigen gleich erscheinen.

Die Natur des Effektes.

Die elementarste Erklärung für den Effekt der Verletzung durch Abschaben läßt sich auf die kinetische Theorie der Materie stützen, nach welcher die wesentlichen Bestandteile gezwungen sind, innerhalb gewisser Konfigurationen zu wirken. Wenn das lichtempfindliche Selen sich im Dunkeln im Gleichgewicht befindet, so sind die in Bewegung befindlichen Teile auf gewisse Konfigurationen oder feste Grenzen beschränkt, vielleicht auf die Grenzen der Kristallflächen. Dieselben Grenzen mögen mehr oder minder bestimmd sein, wenn das Selen dem Licht ausgesetzt wird. Feilen zerstört beispielsweise diese Grenzen, und so beginnen dann die bewegten Teile des Selens, sich neu einzustellen, bis ein neues Gleichgewicht hergestellt ist. Die Teile des Selens müssen die ganze Zeit hindurch in Bewegung sein. Das Schaben bringt nur diese Bewegungen aus ihrer gewohnten Bahn. Die elektrische Leitfähigkeit bezeichnet glücklicherweise beim Selen, ob der Gleichgewichtsstand in gewissen Teilen erreicht ist, oder nicht, oder wie schnell wir uns ihm nähern. Wahrscheinlich erfährt alle Materie mit kristallinischer Struktur infolge von Verletzung ähnliche Veränderungen, aber leider zeigen die meisten Formen der Materie diese elektrische Änderung nicht in ausgeprägtem Maße als Widerspiel.

In zwei früheren Arbeiten über die Wirkung des Lichtes auf das Selen¹⁾) habe ich gezeigt, daß das verschiedenartige Verhalten verschiedener Varietäten des Selens unter der Einwirkung des Lichtes sich durch die Annahme von drei Komponenten erklären läßt, die gemäß der Reaktion $A \rightleftharpoons B \rightleftharpoons C$ im Gleichgewicht stehen. Die Umwandlungsgeschwindigkeiten würden danach bestimmte Werte im Dunkeln und andere im Licht haben. Es mußte angenommen werden, daß die verschiedenen Varietäten des Selens verschiedene Anfangsgeschwindigkeiten der Umwandlung im Dunkeln haben, aber ich habe keine Erklärung dafür angegeben, weshalb dies der Fall sein sollte, d. h. weshalb nicht alle Selenarten demselben Gleichgewichtswerte und derselben Leitfähigkeit im Dunkeln zustreben sollten. Ich habe jedoch die Vermutung geäußert, daß vielleicht bei der Herstellung irgendeiner Varietät des Selens etwas im Selen selbst Liegendes die Ursache dafür ist, daß es gegebene Umwandlungsgeschwindigkeiten beibehält. Nach dieser Anschauungsweise bedingen bestimmte Umwandlungsgeschwindigkeiten bestimmte Konfigurationen, und beide müssen in jedem

1) Phys. Rev. **33**, I, 403, 1911.

Gleichgewichtszustände miteinander gehen. Wenn das Feilen eine bestimmte Konfiguration zerstört, so muß es auch die Umwandlungsgeschwindigkeiten verändern. Der Umstand, daß verschiedene Varietäten des Selens unter denselben Bedingungen hinsichtlich Temperatur, Druck, Feuchtigkeit und elektrischer Verhältnisse verschiedene Umwandlungsgeschwindigkeiten haben können, ist einfach ein Beweis dafür, daß es noch einen anderen Faktor gibt, welcher in verschiedenen Selenproben verschieden ist, und er ist weiter ein Zeichen dafür, daß dieser veränderliche Faktor im Selen selbst liegen kann. Wenn das der Fall ist, so würde der Faktor eine Angelegenheit der Vorgeschichte sein. Es ist wirklich nicht verwunderlich, daß die frühere Behandlung des Selens für seine festen Umwandlungsgeschwindigkeiten sowie auch für seine Eigenschaften bestimmend sein soll. Eine Verletzung durch Schaben löscht vielleicht die Vorgeschichte bis zu einem gewissen Grade aus, und kann vielleicht ein Anwachsen oder eine Umwandlung unter veränderten Bedingungen ermöglichen. Auf alle Fälle müssen wir notwendig das lichtempfindliche Selen als aus veränderlichen und in Bewegung begriffenen Teilen bestehend ansehen, die ein Gleichgewicht erreichen, aber niemals zur Ruhe kommen.

Zusammenfassung.

1. Der Effekt einer Verletzung durch Abschaben ist sowohl für positiv lichtempfindliches als auch für negativ lichtempfindliches Selen untersucht worden.
2. Die beschriebenen Arten der Verletzung rufen eine vorübergehende Zunahme der Leitfähigkeit des Selens der Giltayschen Zelle hervor.
3. Eine Verletzung derselben Art erzeugt eine Veränderung der Leitfähigkeit an negativ lichtempfindlichem Selen, deren Vorzeichen jenem der Veränderung an positiv lichtempfindlichem Selen entgegengesetzt ist.
4. Beide Varietäten des Selens erholen sich von dem Effekt, jedoch langsamer als nach irgendeinem anderen bekannten Agens, das die Leitfähigkeit verändert.
5. Die Änderungen der Leitfähigkeit infolge einer Verletzung sprechen zugunsten gewisser Anschauungen der kinetischen Theorie der Materie.

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EVIDENCE FAVORING THE RADIOACTIVE DISINTEGRATION OF SODIUM AS AN ELEMENT.*

BY F. C. BROWN.

By the usual test for radioactivity, i.e., the continued ionization of a gas independent of other physical conditions, sodium as an element does not display any activity that is definitely greater than that found in all matter. And the ionizing activity of ordinary matter is so slight that it can not be stated with definiteness whether or not the matter is of itself radioactive. But radioactivity implies a more fundamental change than that of emitting matter and energy continuously. It implies an atomis disintegration. If α particles are emitted the atoms go by leaps and bounds to new atoms of other properties, while if β and γ radiations are emitted the wearing away of the atoms must be just as certain, though no one has been able to conjecture by what steps the changes may take place.

The fact that a given element does not give out a measurable ionizing radiation is not necessarily evidence that it is not radioactive. For example we may note the case of Radium C which gives no measurable radiations. Yet it disintegrates or decays to half value in 40 years. It is therefore known as a radioactive element.

If sodium is a radioactive element we may at present look for other evidence than direct radiations. We shall inquire if in past geologic time sodium has accumulated radioactively from other matter or on the other hand if sodium has disappeared or disintegrated into other forms of matter.

THE EVIDENCE FROM GEOLOGY.

The best evidence that we have for considering sodium a radioactive element is from geology. If the age of the earth is determined from radioactive data and the value accepted, we find that there is not accumulated in the ocean basin as much sodium as there should have accumulated during this time.

Different authorities give the age to range between seventy million and one hundred million years. On the other hand, the data of radioactivity gives the age to be about ten times as much as the figures noted above. The principles of the radioactive method are based on the determination of the amounts of helium or lead associated with known quantities of uranium in rocks of different epochs. The two principal assumptions that are involved are that during the age in question the amount of the uranium and its products which give rise to helium shall have remained constant and that the rate of production of helium shall have remained unchanged. Naturally these two assumptions can not be proved. It can only be said that there is no evidence that casts suspicion on these assumptions.

According to experiments by Rutherford and his colleagues, one gram of uranium in equilibrium with its products gives 10.7×10^{-5} cubic centimeters of helium per year. Now if we examine the rocks of the different geological

*This paper was also published in *Le Radium*, in the October number, 1912.

epochs, we find the rare gas helium enclosed in the rock wherever uranium is found, and further the older the rocks the greater is the amount of helium associated with each gram of uranium. Obviously if we divide the total amount of helium per gram of uranium by the above constant, 10.7×10^{-5} , we obtain the number of years during which the uranium has been depositing helium, i.e., the age of the rock containing the uranium.

The greatest chance for error in the above methods of calculation lies in the possible escape of helium from the rock containing the uranium. Therefore the age of the rock as calculated might be too small. The method would therefore set a minimum limit on the age of the earth.

But if we accept Boltwood's conclusion, that the lead associated with uranium in rocks resulted from the radioactive disintegration of the uranium series of elements, and that one gram of uranium gives rise to 1.88×10^{-11} gram of lead per year, we have a check upon the results obtained with the helium deposit. In general the lead deposits give a somewhat larger age for a given rock than do the helium deposits, which is what we should expect if the helium may escape.

Using the method outlined above, Rutherford in 1906, found the age of a sample of fergusonite to be 240,000,000 years. This was deduced as outlined from the fact that 1.81cc. of helium was taken from one gram of the mineral which contained about 7% uranium.

Strutt by the same method found two stones from Quebec of the Archaean age to be 222 and 715 million years old, and two of the same kind from Norway to be 213 and 449 million years. He also found the average minimum value for Haematite of the Eocene period to be 31 million, the same from the carboniferous period limestone to be 150 million years, while for the Archaean age the average was 710 million years.

Holmes using as a basis the ratio of the lead to the uranium in the rocks found the values given in the following table:

Period.	Age.						
Carboniferous	340,000,000 years						
Deconian	370,000,000 years						
Pre-carboniferous	410,000,000 years						
Siluvian	430,000,000 years						
Pre-Cambrian	<table> <tr> <td>Sweden</td> <td>1,025,000,000 years</td> </tr> <tr> <td>U. S.</td> <td>1,310,000,000 years</td> </tr> <tr> <td>Ceylon</td> <td>1,640,000,000 years</td> </tr> </table>	Sweden	1,025,000,000 years	U. S.	1,310,000,000 years	Ceylon	1,640,000,000 years
Sweden	1,025,000,000 years						
U. S.	1,310,000,000 years						
Ceylon	1,640,000,000 years						

The above results show that the age of the earth in its present form must be many times a million years old.

However, if we take the evidence as based on the result that is obtained by dividing the total amount of sodium in the ocean by the annual output of all the rivers of the globe, we find that the age of the ocean can not be more than one hundred million years old. Two of the most eminent geologists, F. W. Clarke and J. Joly, think that 70,000,000 years is much more nearly the correct age based upon the solvent denudation of sodium.

There is therefore a discrepancy between the age of the earth as deduced by the two methods. Joly, in the Philosophical Magazine for September, 1911,

favors the view that the radioactive constants are probably in error, because they have not been taken over data extending over a sufficiently long time, and under proper circumstances free from doubtful assumptions.

I wish to suggest that there is another explanation of the discrepancy that requires no distrust of the radioactive constants as they have been experimentally determined. In fact the explanation is merely an extension of our knowledge of radioactivity to a wider field. The discrepancy disappears if sodium is supposed to be a radioactive element. If we accept the present data of radioactivity as authoritative, then it must be admitted that there is not enough sodium in the ocean. Perhaps during geologic time elements of higher atomic weight may have been disintegrating into sodium, and therefore the annual output of the rivers now is not the average output for all time in the past. That is, the sodium over the land has been increasing by radioactivity production while sodium in the ocean has been increasing almost entirely by the annual river supply. Obviously this would give a greater age for the ocean. Or perhaps the average amount of sodium discharged annually to the ocean has not changed markedly, but that the sodium in the ocean has been very slowly disintegrating into other elements. It seems that our present information is not sufficient to decide which of these two views is most plausible. Either condition is in agreement with an earth of older age. Both conditions may have prevailed, and both ideas are directly in line with recent progress in science. Either is in agreement with further facts as presented by geochemistry.

FURTHER EVIDENCE IN GEOLOGY INDICATING THE DECAY OF SODIUM.

There are other soluble elements than sodium carried to the ocean by rivers, which indicate quite a different age of the earth, and consequently favor the radioactivity of sodium. Only those elements that are not deposited in the ocean bed or otherwise removed from the ocean water may be considered as for reliable information. Clark, in his Geo-Chemistry, second edition, p. 125, gives the following facts; the last column are my own deductions, however:

	Annual output from rivers, metric tonsx10 ³	Amount in the ocean, metric tonsx10 ¹²	Age of ocean
Chlorine.....	155,350	25,538	160x10 ⁹
Sodium.....	158,357	14,138	89x10 ⁹

The geologists do not believe that the rivers carried on the average any less sodium previously than they do now. But if they did, they should also have carried less chlorine. We may therefore for checking purposes say nothing concerning the annual river output further than that it should have varied alike with sodium and chlorine. On this assumption the above figures show that there is not as much sodium in the ocean as there should be. Disregarding the radioactivity data altogether we see that the above evidence favors the radioactive decay of sodium as an element. Clarke goes further to state, "We can understand the accumulation of sodium in the ocean and some of the losses are accounted for, but the great excess of chlorine in sea water is not easily explained. In average river water sodium is largely in excess of chlorine; in the ocean the opposite is true, and we can not help asking whence the halogen element was derived. Here we enter the field of speculation and the evidence upon which we can base an opinion is scanty indeed."

My comment on Clarke's statement would at once give an explanation of the excess of chlorine over sodium in sea water. It is, that if the chlorine has accumulated and disintegrated in the ocean it has been at a much slower rate than has been the disintegration of sodium in the ocean or slower than the decay of the parent of sodium where it was derived from the land.

It is obvious that whether we consider the radioactive data or only the data of geo-chemistry, that it is convenient to assume sodium to be a radioactive element. There has been proposed by no one any other explanation for the discrepancies to which attention is called in this paper. However, it may be noted that the age of the earth as calculated from the chlorine in the ocean is yet much smaller than that given by the radioactive data. I do not believe this discrepancy detracts from the argument as presented.

THE SIMILARITY OF ELECTRICAL PROPERTIES IN LIGHT- POSITIVE SELENIUM TO THOSE IN CERTAIN CRYSTAL CONTACTS.*

BY F. C. BROWN.

Many of the phenomena having to do with the electrical properties of selenium have been regarded as almost unique. Likewise many of the phenomena appearing in connection with the resistance of crystal contacts are considered as unique. Neither of the above sets of phenomena have been explained from a sufficiently simple and satisfactory basis.

It is therefore believed that certain striking similarities in the two above sets of phenomena are significant. The organization of facts in this paper will make it rather convenient to assume that the major portion of the resistance in light-sensitive selenium is of a like nature to the resistance in crystal contacts. The essential phenomena to which attention may be called are as follows:

1. The variation of the resistance with pressure.
2. The apparent invalidity of Ohm's law.
3. The change of resistance with the time of current action.
4. The effect of slight amalgamation.
5. The effect of abrasion.
6. The effect of alternating currents.
7. The breaking down of the resistance by high voltage.
8. The unlikeness of light action.

GENERAL CONSIDERATIONS.

The variations of resistance to be compared appear under apparently different circumstances. In crystal contacts the experiments were usually carried out with a simple crystal in contact with various metals. The surface and manner of contact has been varied in many ways, by using points, and contact surfaces of varying dimensions and treatment. But with selenium the case is more complicated, the crystals are of a very large number and not all of one kind. The current of electricity in selenium must pass through many contacts in series and in multiple

*Paper before A. A. A. S., December, 1912.

with each other. The arrangement of the crystals is probably irregular and complex. So it must be borne in mind that the experiments to be compared are not identical. There is only a general similarity, and the degree of likeness is not definitely known.

THE VARIATION OF RESISTANCE WITH PRESSURE.

That light-positive selenium changes its resistance to a remarkably large amount with pressure was accounted by the author some time ago (Phys. Rev. 20, 185, 1905, also paper by Brown and Stebbins, Phys. Rev. 26, 273, 1908). This large change may be produced by hydraulic pressure applied to the selenium between parallel wires less than one millimeter apart. The effect of pressure was studied more carefully by

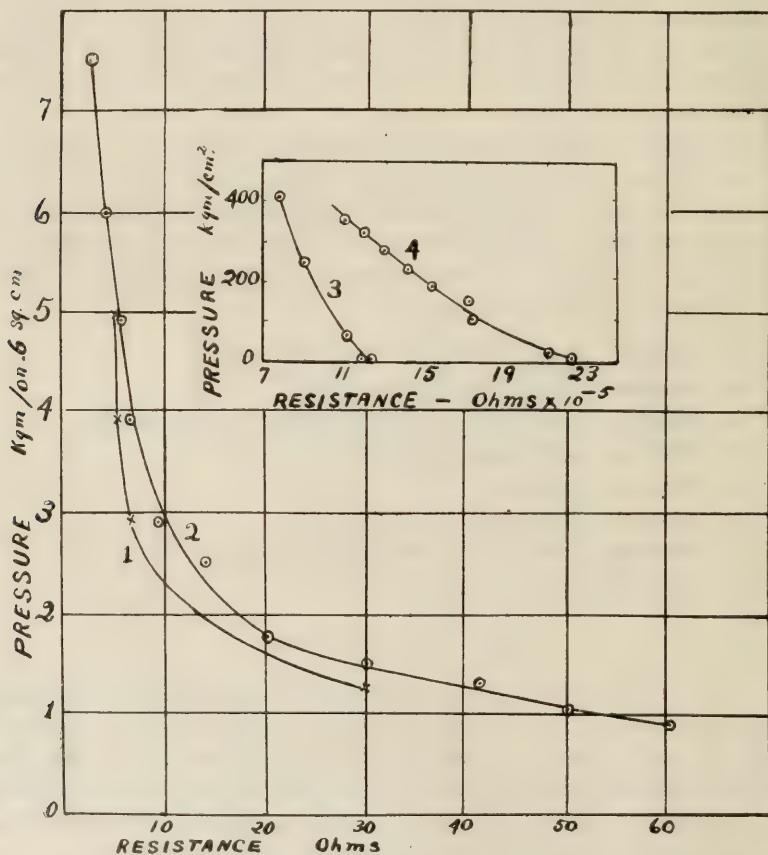


Fig. 1

Monten as given in his dissertation at the University of Uppsala in 1909. According to him the conductivity increases more than seventy times in going from normal pressure up to 3,000 atmospheres. For certain samples of selenium the equation giving the relation between pressure and resistance is

$$R = 2.5 \times 10^6 \cdot e^{-0.00083p}$$

In the lower curve of fig. 1 is given the relation between pressure and resistance for galenite as taken from Streintz and Wellik's paper (*Phys. Zeits.* 12, 848, 1911) where 0.6 volts was the difference of potential across the crystal and its contacts. Curve 2 shows the same relation when 0.41 volts was the potential difference. These curves are typical of what would obtain with many other crystals.

Likewise curve 3 gives the variation of resistance of a selenium cell when the potential difference was 10 volts and curve 4 shows the same relation for 1.4 volts. A glance is sufficient to make obvious the similarity between curves (1), (2) and (3), (4). It will be observed that the pressure-resistance curve for selenium follows approximately the same curve for galenite, where the fall of potential across the latter was 0.41 volts. Evidently the agreement would be better if the fall of potential were yet less in the selenium. This is particularly noticeable at the higher pressures. However this might lead to the assumption that the selenium in the selenium cells is under an initial pressure of several atmospheres due to the packing of the crystals.

The different values for the scale divisions may obviously be explained in one or both of two ways. Either the selenium crystal contact may be inherently of higher resistance than those of the frequently studied crystals or the pressure of a single crystal may be only a small fraction of the pressure per unit area. Supposing the resistance of selenium to be essentially due to contacts and further that the resistance of each contact to vary precisely as it does with galenite, it can easily be deduced that the area of each selenium crystal is approximately .0003 sq. cm. But this assumption and conclusion are purely speculative.

Perhaps the well known change of resistance of carbon granules with varying pressure is more nearly akin to the change in selenium than those referred to in this paper. I have noted however that the resistance of a large number of carborundum crystals when packed under a given pressure is unusually large compared with the resistance of a single crystal contact.

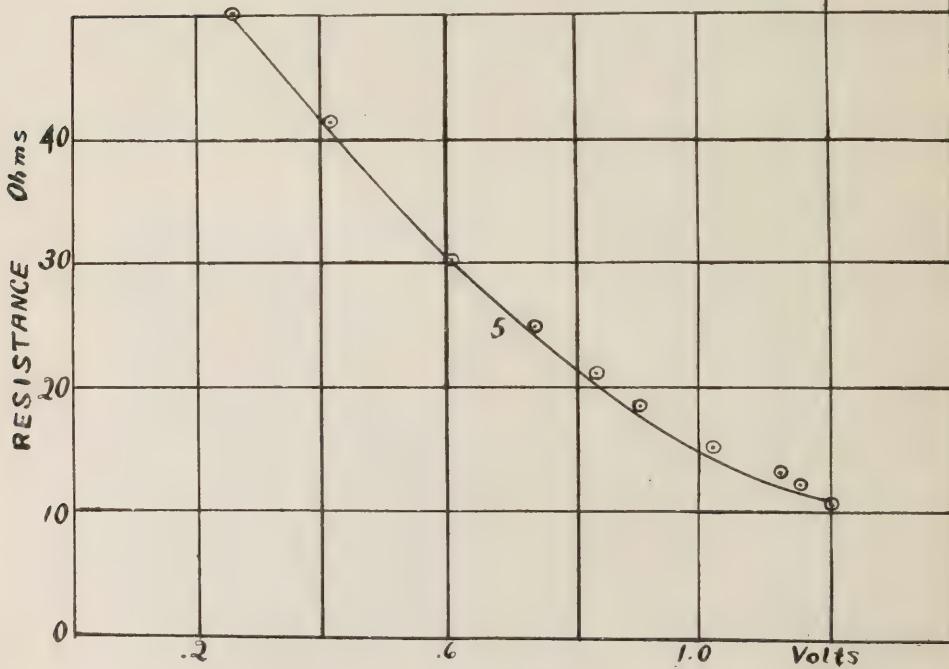
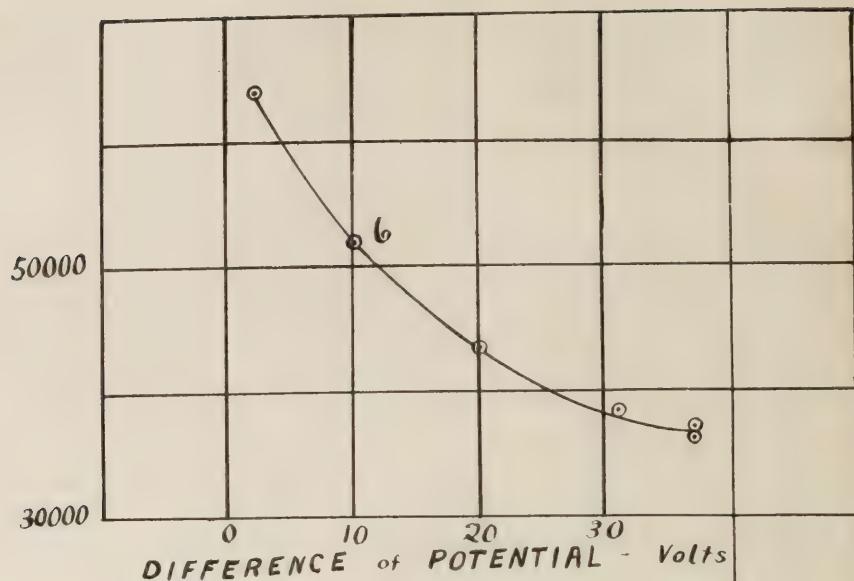


Fig 2.

THE APPARENT INVALIDITY OF OHM'S LAW.

It is well known that the resistance of light-sensitive selenium is a function of the electro-motive force across the circuit. Practically every investigation of crystal contacts has recognized a similar phenomenon with crystals, although the relation has usually been expressed with the resistance as a function of the current. There is no obvious reason why the variations from Ohm's law in crystal contacts as well as in selenium can not arise from a common action. But there is no evidence that shows whether it is the action of the electrical current per se or the electrical stress as indicated by the fall of potential in the circuit, that produces the variation from Ohm's law. I prefer to attribute the change of conductivity in crystals and in selenium to the electric intensity. This notion makes it somewhat easier for me to perceive the relation of the phenomena to the dynamic equilibrium of selenium. In the lower curve of fig. 2 is shown the manner of variation of the resistance of galenite in contact with gold plates* when the potential is varied. The upper curve shows the corresponding variation in light-positive selenium. With the scale chosen the rate of changes of resistance is nearly the same in both instances. Where the potential difference in the selenium changes from 10 to 30 volts, the resistance changes from 50,000 to 38,000 ohms, while with the galenite when the potential difference changes from .2 to .6 volts the corresponding drop of resistance is from 53 ohms to 30 ohms, i. e., with the same ratio of increase of voltage there is not only a decrease of resistance in both, but the percentage decrease is of approximately the same order of magnitude. Perhaps if the data for galenite covered the range from 0.1 to .3 volts we should find the percentage change of resistance more nearly equal to that of selenium. It is noteworthy that the potentials are of the order of 100 times greater in the selenium when the same slope of the curve is approximated. This compares favorably with the increased scale of pressure as shown in fig. 1, necessary for the comparison of the pressure-resistance curves.

THE CHANGE OF RESISTANCE WITH TIME AFTER THE POTENTIAL DIFFERENCE IS APPLIED.

Selenium and crystal-contact resistances present essentially the same behavior by continued application of potential differences across the resistance. In general the resistance of selenium decreases after closing the circuit as it does in crystal contacts. According to Pierce if (Phys. Rev. borundum and then in the same manner the voltage is decreased, it is

*Streintz and Wellik Phys. Zeits loc cit.

found that the same ratio does not exist between volts and amperes in the two instances. The current is larger after the maximum voltage has been applied. Pierce describes it as a slow building up of the current. In a later paper he quotes Braun on (Phys. Rev. 29, p. 478, 1909) the subject, in part as follows: "I obtained in general the phenomena that the current (25 p. 36, 1907) first voltages increasing step by step, are applied to the circuit closed; the current strength was different for different directions of the current; and that this difference increased with increase of the current, and then on keeping the circuit closed, the current for that direction in which the resistance was smaller increased, while for the opposite direction it decreased."

With selenium the usual occurrence is for the resistance to decrease with the time of flow of the current but this is not always true. In a former paper (Phys. Rev. 33, p. 21, 1911) I gave results which showed first an increase followed by a decrease of resistance for a high voltage. This held only with the selenium in the Giltay cell.

THE EFFECT OF AMALGAMATION.

It was first observed by Moss (Proc. Roy. Soc. XXV, p. 22, 1876, and Nature 77 p. 198, 1908) that mercury decreases the resistance of selenium in a rather peculiar manner. A small amount of mercury according to him forms a film over the crystals of the selenium and renders the cell thereby quite conducting. More recently Minchin contended with the same effect under other circumstances. A certain selenium cell had a resistance of 61×10^6 ohms in the dark at atmospheric pressure. (Nature, 77 p. 222, 1908.) In a vacuum with a partial pressure of mercury vapor the resistance fell to 17.5 ohms in 12 hours. More recently the author has outlined the extent and the (Phys. Rev. Ser. 2, Vol. 2, p. 153) probable nature of the action of mercury vapor on selenium. However the important feature in this connection is the remarkable increase of the conductivity, and the light-negative characteristics called forth by the mercury.

Likewise if amalgamated surfaces are brought in contact with certain crystals the contact resistance of the crystal disappears almost entirely, and only the resistance of the crystal itself may remain. Streintz and Wellik* call attention to a magnetite crystal which had a resistance of 0.17 ohms under a pressure of 3000 gms when the contacts were of gold. The resistance of this specimen fell by using gold-amalgam contacts from 0.17 to 0.008 ohms. This result is also typical of what is obtained by

*Phys. Zeits, 12 p. 845, 1911.

using amalgamated surfaces, according to Koenigsberger, Reichenheim and Schilling.* But we can not be certain that mercury acts in the same way in selenium that it does with other crystals. If a small globule of mercury is put on a crystal surface* the contact resistance will not be destroyed. It is probable that the surface tension of the mercury keeps the globule from making the intimate contact that is made by the amalgam under pressure. A gold electrode in contact with a crystal of galenite had a resistance of 50 ohms with 150 gms pressure. After the gold was amalgamated the resistance was .067 ohms with 150 gms pressure and .057 ohms with 1224 gms. The change of resistance with pressure and with the current is comparatively very small after amalgamation. This together with the fact that the change of resistance by pressure is greater than the resistance of the crystal itself, furnishes almost a conclusive proof that the pressure effect and the current effect is of the nature of a change of resistance at the point of contact with the crystal.

In selenium the mercury vapor forms mercuric selenide. Whether it is this selenide or the free mercury molecules or semi-free molecules in the selenide, that makes the light conductivity can not be definitely settled yet. However, if we take amorphous selenium and let the mercury vapor act on it, we obtain almost as high a conductivity if only about one per cent of the selenium is acted upon as we do if the entire quantity of selenium is transformed into selenide. This is very much in favor of the presumption that it is the free or free acting mercury molecules that is responsible for the very high conductivity. The speculation that we may find it convenient to make is that mercury in a finely divided state may bring about the same action in crystal contacts that it does in selenium. The presumption is based on the apparent similarity of the effects.

THE EFFECT OF ABRASION.

In two earlier papers* I have described the effect of rupturing the surface of light-sensitive selenium by abrasion. The immediate effect of the abrasion is to increase the conductivity. This effect is likewise duplicated in crystal contact resistance. I may quote from Flowers,* "A crystal having a rectifying surface was often found to have other rectifying surfaces underneath and parallel when the layers were split

*Phys. Zeits, 12 p. 11, 39, 1911.

*See paper by Alan E. Flowers on crystal and contact rectifiers, Phys. Rev. 29, p. 451, 1909.

*F. C. Brown, Phys. Rev. 34, 201, 1912, Phys. Zeits. 1912.

*Phys. Rev. 29, p. 453, 1909.

off, but scratching or scarring a rectifying surface usually spoiled more or less completely its rectifying properties. In order to destroy the rectifying properties, the resistance must have changed in one direction or the other." However, he does not state whether mutilation increased the resistance that was least or decreased the resistance in the direction of largest value. I assumed that he meant the latter. However, in order to be more certain I experimented with a crystal of galenite which had slightly greater resistance in one direction than in the other. I rubbed one contact surface quite vigorously with rouge on chamois cloth. This caused the resistance to decrease about ten times. After several months the crystal did not recover from this abrasion, but no doubt it would do so in time.

It is, therefore, obvious that abrasion produces certain very similar results in crystals that it does in selenium.

THE EFFECT OF ALTERNATING CURRENTS.

Alternating currents produce varying results depending upon the light-sensitive selenium and the frequency of the current. Certain frequencies have been noted to decrease the resistance while other frequencies have increased the resistance. Alternating currents produced effects in crystal contacts that might be regarded analogous to those in selenium. However, we should investigate the exact conditions of the phenomena before we can presume as to the likeness of the effects.

THE BREAKING DOWN OF THE RESISTANCE BY HIGH VOLTAGE.

If a very high voltage is applied across a light-sensitive selenium all the resistance breaks down and the light sensitiveness is destroyed. Ordinarily the voltage from the secondary of an induction coil is necessary for this result. Just how much lower the potential might be I am not certain.

In crystal contacts a potential difference of 30 or 40 volts is almost certain to break down the resistance. However, this potential is partly determined by the pressure on the crystal surface and the number of contacts in series. A number of crystals in series approach more nearly to the conditions existing in selenium.

THE ANTIMONITE CELL.

If we could establish like behavior between crystal contact resistances and the selenium cell, when the two are illuminated, we should have a strong presumption in favor of the identity of the two sets of phenomena.

But thus far I have not been able to detect any change of resistance in crystal contacts because of any direct or even indirect action of light. At present my hope is that I may find some crystal or crystals that change form or volume under the action of light. If such are packed among small crystals that show resistance because of the surface contacts, then we should have a variation of the resistance of the mixture by illumination by virtue of the change of pressure. Theoretically we should be able to produce in this way an approximate working model of a selenium cell.

It may be that W. S. Graepenberg has duplicated the action of the selenium cell in his antimonite, a mixture of antimony and sulphur. By properly cleaving these crystals he is able to produce a light-sensitive cell. The resistance is apparently like that in ordinary crystal contacts in that the resistance exists between a gold foil and the surface of the crystal. The crystal is illuminated through the gold foil. This cell structure is about as sensitive to light as the selenium cell and it seems to have all the properties common to both selenium and crystal contacts. But so far as I am at present able to judge, it is only surmised that antimonite crystals bridge over the gap. If we should find definitely a crystal or crystal mixture which was known to be light-sensitive like selenium and at the same time know that its resistance depends on contact surfaces, we should have a new and very simple approach for explaining the complex behavior of selenium. A curve showing how the resistance of the antimonite cell varies with potential difference is given in fig. 3. This is strikingly similar to such curves for selenium and elementary crystal contacts.

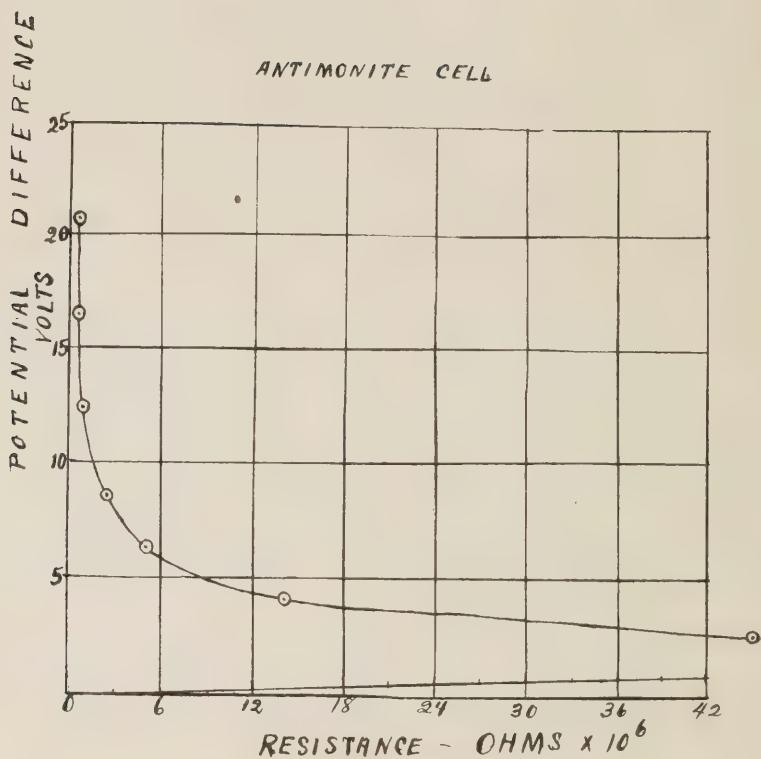
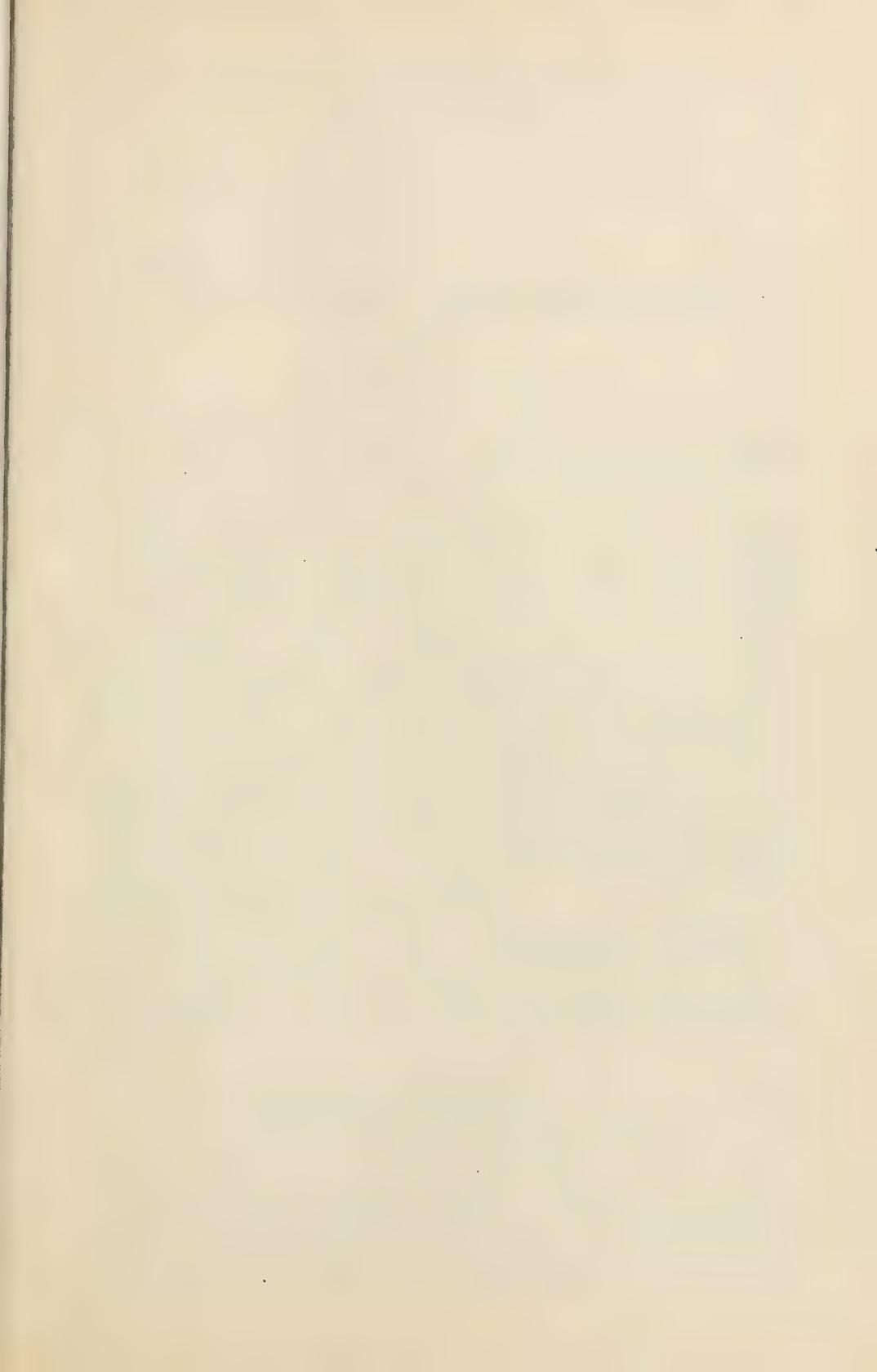


Fig. 3



A METHOD OF PRODUCING KNOWN RELATIVE SOUND INTENSITIES AND A TEST OF THE RAYLEIGH DISK.

By G. W. STEWART AND HAROLD STILES.

THE absolute intensity of sound has been measured principally in four ways, viz., by the use of the Rayleigh disk placed directly in the sound,¹ by the measurement of the increased pressure at a reflecting wall,² by measuring pressure changes at nodes of stationary waves by a manometer,³ and by optical interference methods.⁴ In some of the experiments to which reference has just been made, varying measurable sound intensities have been produced, but in such a manner as to be unavailable for the calibration of intensity measuring devices of various kinds. Indeed, we have found no record of a successful effort to produce known varying intensities available for testing purposes. The application of the inverse square law is quite inaccurate, even out of doors. The construction of a sound-proof or a "silence" room will probably not reduce the reflection sufficiently to justify the assumption of the variation of the intensity inversely as the square of the distance.

The theory⁵ of the acoustic shadow produced at any distance from a rigid sphere with the source located on the sphere suggested a method of producing known variations of intensity and thus obtaining a calibration device for sound-measuring apparatus.

The theory can be briefly stated. Let the source be confined to a small area on the surface of the sphere within which $P_n(\mu) = 1$. Let the velocity of this source region be simple harmonic and let it have the same magnitude U throughout. The following notation and equations are assumed:

- ψ represents the velocity potential,
- a represents the velocity of sound,
- r represents the distance from center of sphere,
- c represents the radius of the sphere,

¹ Zernov, Annal. d. Phys., 26, 1908, p. 79, Fig. 10.

² Altberg, Annal. d. Phys., 11, 1903, p. 405, and Zernov, Annal. d. Phys., 21, 1906, p. 131.

³ Raps, Annal. d. Phys., 36, 1889, p. 273.

⁴ Raps, Annal. d. Phys., 50, 1893, p. 193, and Sharpe, Science, 9, 1910, 1909, p. 808.

⁵ Stewart, PHYS. REV., Vol. XXXVIII., No. 6, December, 1911.

dS represents an element of surface,

$$K = \frac{2\pi}{\text{wave length}},$$

$$\gamma = k(at - r + c),$$

$$F = \sum \frac{2n+1}{2} P_n(\mu) \frac{\alpha\alpha' + \beta\beta'}{\alpha^2 + \beta^2},$$

$$G = \sum \frac{2n+1}{2} P_n(\mu) \frac{\alpha\beta' - \alpha'\beta}{\alpha^2 + \beta^2},$$

$$^2f_n(ikr) = \alpha' + i\beta',$$

$$^2F_n(ikc) = \alpha + i\beta.$$

Then

$$\psi = \frac{ka}{2\pi r} (F \sin \gamma + G \cos \gamma) \iint U dS. \quad (1)$$

The energy per unit volume is $\frac{1}{2}\rho_0 a^2 s^2$, where ρ_0 is the density and s the condensation. But s equals $-\dot{\psi}/a^2$. Therefore we have for the mean potential energy the following expression,

$$\text{Energy per unit volume} = \frac{1}{2}\rho_0 \frac{\dot{\psi}^2}{a^2} = \frac{1}{2}\rho_0 (F^2 + G^2) \left(\frac{k}{2\pi r} \iint U dS \right)^2. \quad (2)$$

We determined to construct a sphere with a satisfactory source of sound thereupon, and thus to secure in the region of the sphere varying sound intensities of known relative values.

As shown in Fig. 1 the sphere was mounted on the edge of the roof of the Physics Building. It was placed on the side where the building was 21 meters high. There were neither buildings nor trees within several hundred feet, and this, combined with the high elevation, made the location very satisfactory. Indeed, the only reflecting surface was the roof. The arrangement of the apparatus shows that the error due to the reflection from the roof would be very small, and this error was further reduced by a covering of three fourths of an inch of hair felt.

The sphere was constructed of cement, the wall thickness being 5 cm. The diameter of the opening, the source of sound, was about 5 cm. The circumference of the sphere was 135.9 cm. As shown by the figure, the sphere could be rotated readily, the angle being indicated at the water seal. The sphere was supported by a horizontal 5 cm. pipe 230 cm. above it, and this pipe was in turn supported by two 5 cm. pipes and an iron flagstaff, all three being distant from the sphere at least 250 cm. The reflection from these supports was practically nil.

¹ $f_n(ikr)$ and $F_n(ikc)$ are defined in Rayleigh's Theory of Sound, Vol. II., and in article by Stewart, loc. cit.

The sound was produced by an electromagnetically operated tuning fork mounted on a resonator, the latter being introduced into a funnel located at a distance of 700 cm. from the sphere and connected to it through an iron pipe as suggested by Fig. 1. The frequency used was 256, and thus kc was very approximately unity.

The apparatus to the left of the sphere in Fig. 1 is a Rayleigh disk

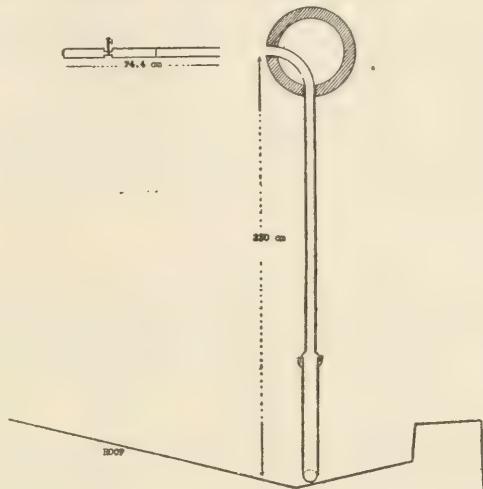


Fig. 1.

device. This was used to prove the practicability of this method of producing known relative intensities. This device is a modification of the one suggested by Rayleigh¹ and is drawn to scale in Fig. 2. It was made of brass tubing. The constriction in the tube was introduced to increase the sensitiveness. The dimensions needed were calculated by an approximate formula and then tested experimentally before constructing the apparatus.

The mirror, 0.6 cm. in diameter, was made from a very thin microscope

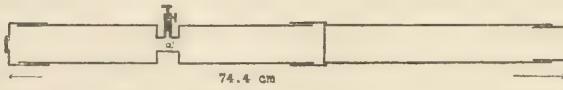


Fig. 2.

cover glass. It was suspended by a quartz fiber. The complete period was 6 seconds.

The observing telescope was placed along the axis of the tube and the scale parallel to the tube and in front of the mirror window. The apparatus had a high sensibility giving a definite deflection for what would be

¹ Rayleigh, *Phil. Mag.*, Vol. XIV., p. 186, 1882.

termed a "faint" sound. The sensitiveness could have been increased greatly by reducing the size of the fiber suspension, but for work out-of-doors a short period was highly desirable.

The diaphragm was a piece of thin letter paper, but the selection of this material has no significance as it was not the result of investigation. The Rayleigh disk as used undoubtedly gives a deflection which is practically proportional to the kinetic energy on the interior at the disk itself. Indeed this has been demonstrated¹ experimentally. So far as we have been able to ascertain there is no experimental evidence that the kinetic energy at the disk itself is proportional to the potential energy which would exist at the opening of the resonating tube if the presence of the apparatus produced no distortion. Yet we here tentatively assume this to be the case. In this paper "energy" refers to potential energy unless otherwise designated.

We used the disk at three distances, viz., $kr = 2$, $kr = 3$, and $kr = 4$. The computations for these distances were made in accord with the formula (2) and the relative values of $F^2 + G^2$ obtained. The values for $f_n(ikr)$ and $F_n(ikc)$ were computed from equations defining these expressions.²

The values of the terms of Legendre's series $P_n(\mu)$ for the angles used from 0° to 180° were ascertained from tables and the relations

$$P_{2n+1}(90^\circ + \theta) = P_{2n+1}(90^\circ - \theta)$$

and

$$P_{2n}(90^\circ + \theta) = P_{2n}(90^\circ - \theta).$$

The terms were retained as far as $P_6(\mu)$. The computations are probably sufficiently accurate for the purposes of this paper. The results are shown in the accompanying tables.

The accompanying curves (Fig. 3 and Fig. 4) show these computations plotted with the value at 0° taken as unity. This is the position of the sphere when the source of sound is directly in front of the Rayleigh disk. The points indicated by small circles are the results of observations with the Rayleigh disk. The relative deflections are plotted. Our maximum deflection from the 45° position of the disk (*i. e.*, 45° between the normal to the mirror and the direction of the undisturbed stream) was 7° . An inspection of the formula³ derived for the disk shows that the assumption of proportionality of energy to deflection does not introduce an error we need here consider.

¹ Zernov, Annal. d. Phys., No. 26, p. 79, 1908.

Stewart, loc. cit.

³ Konig, Wied. Annal., XLIII., 1891, p. 51.

TABLE I.

 $kc = 1, kr = 2$.

	0°		30°		60°		90°	
	F	G	F	G	F	G	F	G
0	+0.2500	-.2500	+.2500	-.2500	+.2500	-.2500	+.2500	-.2500
1	+.7500	.0000	+.6495	.0000	+.3750	.0000	.0000	.0000
2	+.3020	+.2669	+.1887	+.1669	-.0377	-.0334	-.1510	-.1335
3	+.0949	+.1352	+.0308	+.0439	-.0415	-.0591	.0000	.0000
4	+.0398	+.0616	+.0009	+.0014	-.0115	-.0178	+.0150	+.0231
5	+.0188	+.0292	-.0042	-.0065	+.0017	+.0026	.0000	.0000
6	+.0091	+.0142	-.0034	-.0053	+.0029	+.0046	-.0029	-.0044
	+1.4646	+.2571	+1.1123	-.0496	+5.389	-.3531	+1.1111	-.3648
$F^2 + G^2$	2.2111		1.2397		0.4151		0.1454	
	120°		150°		180°			
	F	G	F	G	F	G		
0	+.2500	-.2500	+.2500	-.2500	+.2500	-.2500		
1	-.3750	.0000	-.6495	.0000	-.7500	.0000		
2	-.0377	-.0334	+.1887	+.1669	+.3020	+.2669		
3	+.0415	+.0591	-.0308	-.0439	-.0949	-.1352		
4	-.0115	-.0178	+.0009	+.0014	+.0398	+.0616		
5	-.0017	-.0026	+.0042	+.0065	-.0188	-.0292		
6	+.0029	+.0046	-.0034	-.0053	+.0091	+.0412		
	-.1315	-.2401	-.2399	-.1244	-.2629	-.0717		
$F^2 + G^2$	0.0749		0.0730		0.0742			

The agreement between the theory of the acoustic shadow and the performance of the disk is not good in Fig. 3 for $kr = 2$, but is quite satisfactory in Fig. 4, $kr = 3$, conditions considered. If the disk itself were suspended in the open air it would give correct relative values of the mean kinetic energy per unit volume at the point. But the disk is enclosed in order to utilize the magnifying effect of resonance. This introduces several sources of error. A slight breeze interferes with the resonance of the tube, and doubtless this error has not the same relative value for all values of resonance. We worked under the best conditions obtainable and yet there was always a perceptible motion of the atmosphere. Our observations indicate that the small readings were greatly in error. It should be stated that the observed points are not averages of large numbers of readings, but represent different sets of observations. Another source of error is introduced by the absorption of energy by the resonating disk tube. This must disturb the distribution of sound intensity. It would seem that this distortion would tend to "iron out" the curve, or to produce higher readings on the steeper portions. One would also expect the distortion at $kr = 3$ to be less than at $kr = 2$.

TABLE II.

 $kc = 1, kr = 3.$

	0°		30°		60°		90°	
	F	G	F	G	F	G	F	G
0	+0.2500	-0.2500	+0.2500	-0.2500	+0.2500	-0.2500	+0.2500	-0.2500
1	+0.7000	+0.1000	+0.6062	+0.0866	+0.3500	+0.0500	0.0000	0.0000
2	+0.1311	+0.2904	+0.0819	+0.1815	-0.0164	-0.0363	-0.0656	-0.1452
3	-0.0122	+0.0876	-0.0039	+0.0285	+0.0053	-0.0383	0.0000	0.0000
4	-0.0082	+0.0212	-0.0002	+0.0005	+0.0024	-0.0061	-0.0031	+0.0079
5	-0.0026	+0.0057	+0.0006	-0.0013	-0.0002	+0.0005	0.0000	0.0000
6	-0.0008	+0.0017	+0.0003	-0.0007	-0.0003	+0.0006	+0.0003	-0.0005
	+1.0573	+0.2566	+0.9349	+0.0451	+0.5908	-0.2796	+0.1816	-0.3878
$F^2 + G^2$	1.1841		0.8760		0.4274		0.1834	
	120°		150°		180°			
	F	G	F	G	F	G		
0	+0.2500	-0.2500	+0.2500	-0.2500	+0.2500	-0.2500		
1	-0.3500	-0.0500	-0.6062	-0.0866	-0.7000	-0.1000		
2	-0.0164	-0.0363	+0.0819	+0.1815	+0.1311	+0.2904		
3	-0.0053	+0.0383	+0.0039	-0.0284	+0.0122	-0.0876		
4	+0.0024	-0.0061	-0.0002	+0.0005	-0.0082	+0.0212		
5	+0.0002	-0.0005	-0.0006	+0.0013	+0.0026	-0.0057		
6	-0.0003	+0.0006	+0.0003	-0.0007	-0.0008	+0.0017		
	-0.1184	-0.3040	-0.2709	-0.1824	-0.3131	-0.1301		
$F^2 + G^2$	0.1065		0.1065		0.1150			

This expectation seems to be realized in the observations as shown in Figs. 3 and 4.

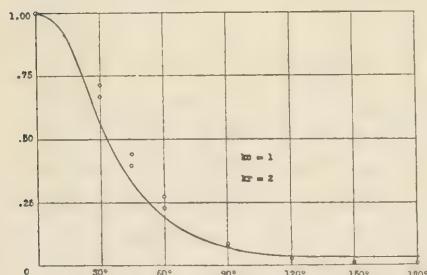


Fig. 3.

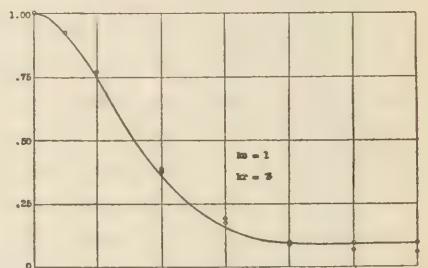


Fig. 4.

The theory, equation (2), shows that the intensities at different distances are proportional to $(F^2 + G^2)/r^2$. The results of a brief test at three different distances, $kr = 2$, $kr = 3$ and $kr = 4$, are presented in the accompanying table.

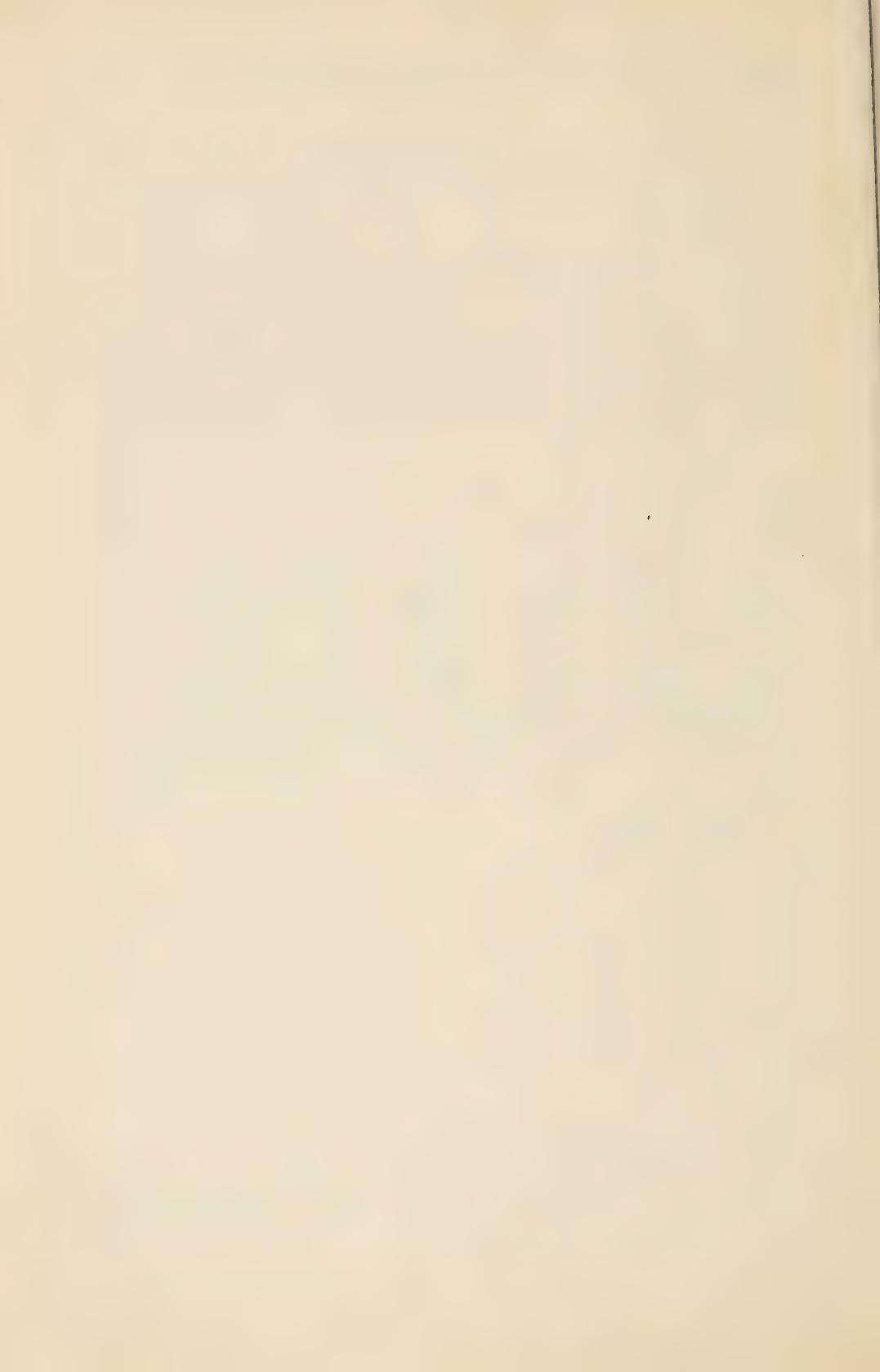
TABLE III.

kr	$F^2 + G^2$	$A = \frac{F^2 + G^2}{r^2}$.	$B = \text{Deflection.}$	Ratio of A to B .
2	2.206	0.551	11.80	21.4
3	1.145	0.127	2.80	22.0
4	0.915	0.0572	1.28	22.4

The theory is verified in that the ratio between the observed and theoretical relative values is practically constant. It is interesting to note that if the observed values are tested in a similar manner, but assuming the inverse square law, the results for the last column differ as much as 130 per cent.

The results presented in this paper certainly demonstrate that the method of producing known relative sound intensities is a practicable one, although attended with some difficulty of operation and limited both by the absorption of the instrument to be calibrated and the inconstancy of the source of sound. So far as the experiments with the Rayleigh disk are concerned, the results may be regarded in either of two ways. One may consider that they show the theory to be correct, assuming the deflection of the Rayleigh disk to be proportional to the energy. The writers, however, regard the theory of the acoustic shadow as more reliable than the assumption as to the action of the disk. The experiments call attention to certain errors in the operation of the disk which are unavoidable in any measuring instrument which utilizes resonance.

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THE SIGNIFICANCE OF INTENSITY—SUM IN BINAURAL LOCALIZATION.

By G. W. STEWART.

IN the various contributions on sound localization, numerous references have been made to the *difference in intensities* at the ears as an important factor in sound localization. That it is an important factor none can dispute, but there is no evidence that it is the most important intensity factor. The object of this paper is to consider the *sum of intensities* as a factor in practical localization. Obviously the relative importance of these two factors depends upon the conditions imposed in the experiments. If the head and the source of sound are stationary, then the intensity-difference and intensity-ratio are probably the only intensity factors. But if the observer is allowed to turn his head at will and if the sound is of sufficient duration, then he has the opportunity of comparing different intensity-sums with different positions of the head.

Theory.—In a previous theoretical investigation¹ the writer assumed that the apparent intensity of sound was the sum of the intensities at the two ears, phase not being considered, and accordingly curves were plotted showing the variation in this intensity-sum with different positions of the head. The character of the dependence of this variation upon wavelength was so different from that of intensity-difference and intensity-ratio and so unexpected withal that an experimental test was arranged to show whether or not the intensity-sum is a factor of importance. The results of the theoretical investigation of intensity-sum are reproduced in Fig. 1. Here the ordinates are relative values, unity at 0° , for the intensity-sums with different wave-lengths, and the abscissæ give the position of the head, 0° being the position with an ear toward the source, 90° the position with the source directly in front, and 180° with the other ear toward the source. The distance of the sound source is 477 cm. In the assumption involved in the theory, viz., that the head is a rigid sphere with the ears diametrically opposite, there is no distinction between front and rear and therefore the rotation of the head from 180° to 360° is secured by duplicating the curves shown in Fig. 1.

The results for wave-lengths of 240, 120 and 60 cm. are not surprising when one considers that with the shorter wave-lengths the head is more

¹ Stewart, PHYS. REV., XXXIII., No. 6, December, 1911, p. 467.

of an obstacle. That the curve for 30 cm. did not follow this general trend was a surprise. A check on these results is obtained from the results of Lord Rayleigh for a source at a great distance, for the variation

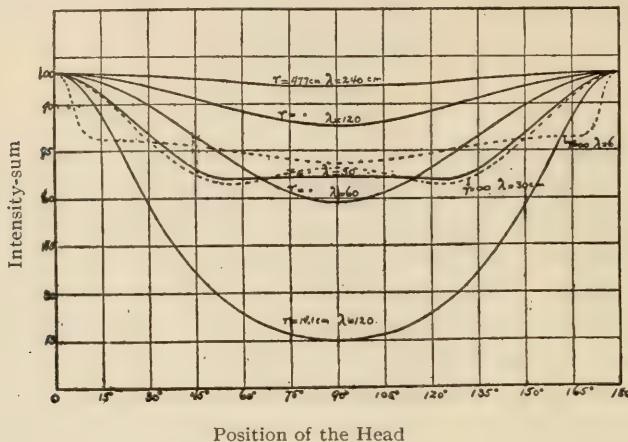


Fig. 1.

in intensity in the shadow of the head with the source at 477 cm. is not greatly different from that with the source at a great distance.¹

The intensity-sums obtained from Lord Rayleigh's results are represented in the figure by dotted lines. These additional curves also indicate that a curve obtained for a wave-length of 6 cm. would show a greater flattening. More theoretical curves would have been computed if the computations had not been very laborious or if there had been any doubt in regard to the conclusions that can be drawn.

The intensity-differences and intensity-ratios give curves of a very different character. Fig. 2 gives the results of such computations, utilizing the same values of intensities as before. The meaning of 0° and that of 90° are the same as before. It is obvious that these two sets of curves are similar in that the effect of changing the wave-length is a progressive one. In this respect they are not like the curves in Fig. 1. If the intensity-sum is of practical importance in the localization of sound, then the observer, when facing the source (90°), should have less difficulty in locating a source of wave-length 60 cm. than one of wave-length 30 cm. or 120 cm., for with the first named there is a greater variation of the intensity-sum with a given small rotation of the head, than with either the 30 cm. or 120 cm. wave-length. In other words, when the observer faces the source of sound, a given variation of intensity-sum is ob-

¹ Stewart, loc. cit.

tained with a less rotation of the head in the case of a wave-length of 60 cm. The curves do not show that 60 cm. is the "critical" wave-length. Additional curves would need to be plotted to get nearer the truth in this respect. But Fig. 1 does indicate that there is a critical wave-length. The question to be determined experimentally is whether or not this theoretical deduction can be observed in practice. If it can be observed then the intensity-sum must be an important factor in practical sound localization. But more than this. The curves in Fig. 2 indicate that

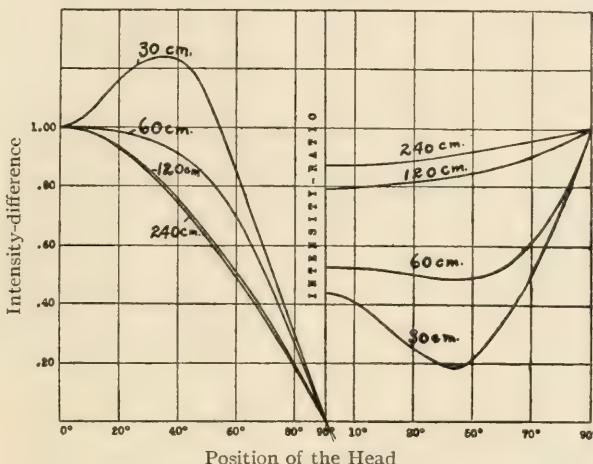


Fig. 2.

when the observer faces the source and rotates the head through a small angle, there is the greatest change with the smallest wave-length, since in each set of curves the slope for the 30 cm. curve is the greatest of the four at 90°. It would therefore seem that a search for this critical wave-length indicated in Fig. 1 would determine whether or not the intensity-sum theory is of greater importance under usual circumstances than either the intensity-difference or intensity-ratio theory. It seems to be a matter of common experience that very low or very high pitch tones are the most difficult to locate, but this is not sufficient to prove the point.

Experiment.—In a room with reflecting walls sound localization becomes a very complex problem. Experiments in the open air without reflecting surfaces are practically impossible. The results here recorded were obtained upon an open piece of ground thickly covered with grass. The sources of sound were tuning forks mounted upon resonators. No accurate measure of ability to localize was sought. The degrees of ability were graded in an arbitrary manner.

Any of the observers could without difficulty point directly to the

source of sound, so readily were all the tones localized. When the observer, facing the source of sound 477 cm. distant, was asked to rotate his head back and forth and to indicate with a large pair of dividers the angle within which the sound seemed to be located with certainty, he found no serious difficulty in reaching a conclusion. The observer made his adjustment of the dividers with his eyes closed and the distance between the points of the dividers was taken as a measure of the angle within which the sound was definitely located. The angle varied with different tones. The results obtained are presented in Fig. 3.

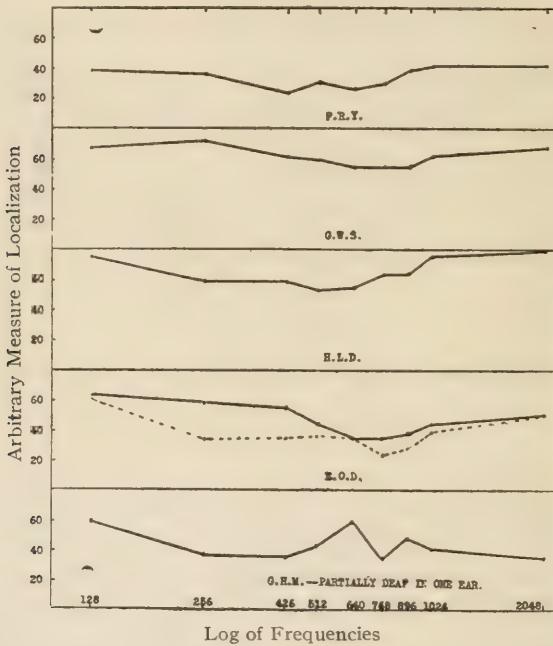


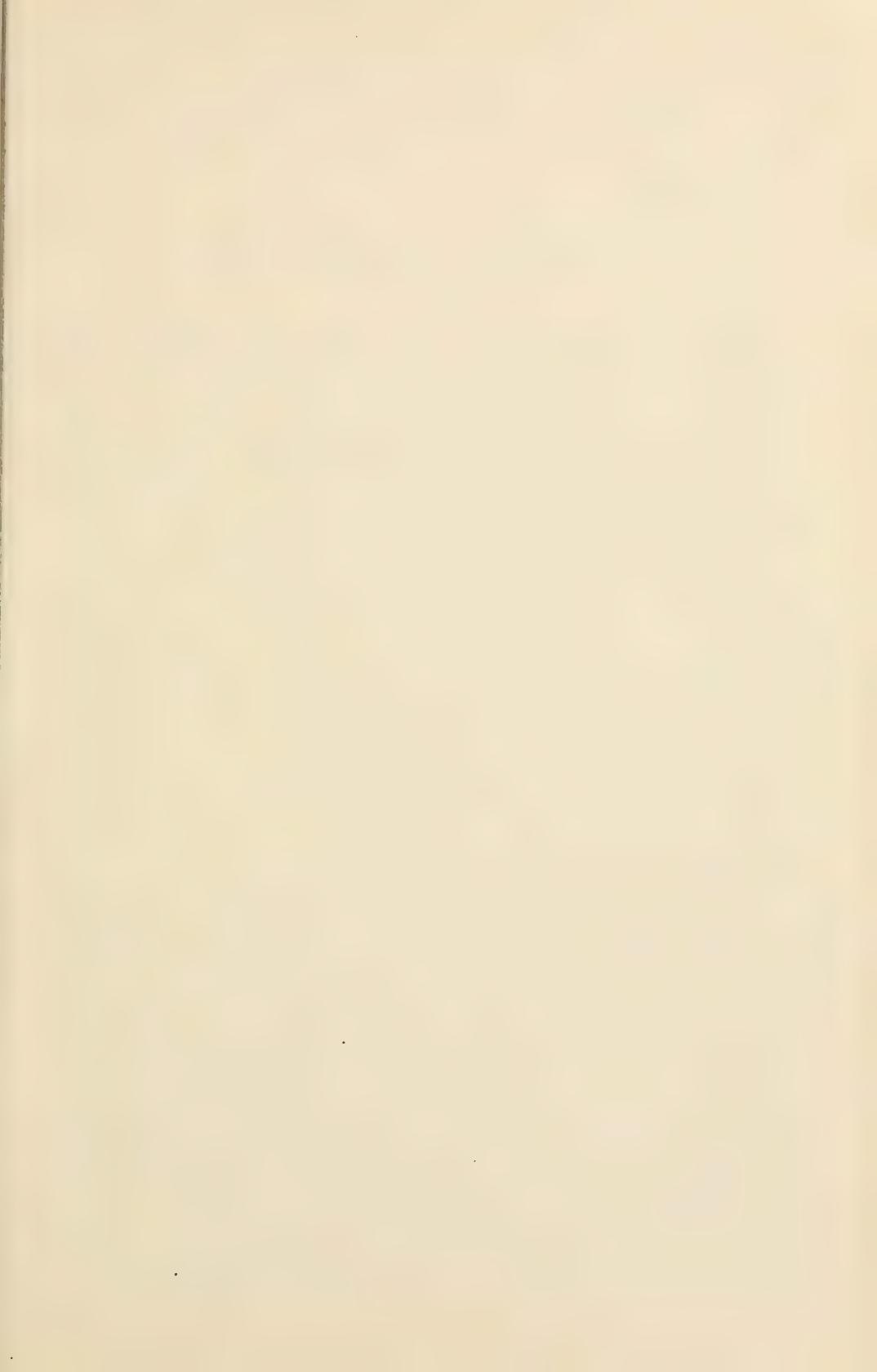
Fig. 3.

Nine forks were used and any order of presentation was carefully avoided. The results are averages of several observations for each fork. The observations of the first three are satisfactory. The observations of the fourth set, E. O. D., were taken upon windy days and were not satisfactory to the observer. The full line and the dotted line represent the results of experiments on different days. The fifth observer was partially deaf in one ear. In this case the curve shown is not obtained from a large number of observations but indicates in a general way the irregularity of his observations. The curve strengthens rather than weakens the conclusions derived from the other curves. The

existence of a minimum is obvious for the percentage change in the arbitrary measure of angle of localization is very great. In fact in some cases the change is 100 per cent. of the minimum.

Although the experiments are somewhat crude and should be carried out with greater degree of accuracy, the results are unmistakable. The curves show that the frequency 512 to 640 is localized with the greatest accuracy, a confirmation of the theoretical deductions based upon the intensity-sum as a factor. That is, there is a critical wave-length in the neighborhood of 60 cm., frequencies 512 to 640. An inspection of the curves for intensity-differences and intensity-ratios shows that neither of these possible factors furnish an explanation of the experimental results, that indeed they would point toward very different results. The conclusion is that the intensity-sum is an important factor in practical localization where the observer can and does rotate the head in the interval of the sound duration. Indeed, the confirmation is so definite that one is inclined to believe that, in practical localization, the intensity-sum is the most important intensity factor.

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THE ACTION OF MERCURY VAPOR ON SELENIUM.

BY F. C. BROWN.

PREVIOUSLY¹ I have shown that all the known changes of conductivity of selenium with the time of exposure to light can be explained mathematically by assuming a dynamic equilibrium between three components *A*, *B* and *C*. But in this analysis there appeared an obvious physical interpretation of the varying initial rates of change which were imposed on the different varieties of selenium for equilibrium in the dark. This fact has led the author to search for the conditions which will consistently and certainly produce one of the varieties of selenium about which there is most dispute, viz., light-negative selenium. The question as to whether the light-negative property is in the selenium itself or is in impurities, or selenium compounds, was one that had to be definitely settled. While the search has not answered all questions that have arisen, it has proved worth while in that it has resulted in some definite advances, that are interesting and which further limit future investigations. It is found that mercury vapor will uniformly transform different allotrophic modifications of selenium into light-negative selenium, and further that the mercury vapor probably forms chemical union with the selenium.

In considering a relationship which I observed between the conductivity of selenium and its sensibility, viz., that light-negative selenium is associated with high conductivity, it occurred to me that any method that produces low resistance selenium might also at the same time produce light-negative selenium. In this connection it was noted that Moss² and later Minchin³ had observed the remarkable decrease of resistance of selenium when it was placed in a vacuum produced by a mercury pump. Moss first exposed a bar of vitreous selenium to mercury vapor in a partial vacuum, whereupon he observed that the conductivity increased to a higher value than that of any known modification of selenium. He attributed this conductivity to a mercury film, and consequently it is not surprising that he overlooked the negative action of light. Minchin placed a light-positive selenium cell in a Sprengel vacuum. He observed that cells of several hundred thousand ohms decreased in resistance in

¹ PHYS. REV., 33, pp. 1 and 403.

² Phil. Mag., Ser. 5, 3, p. 67, 1877.

³ Nature, 77, p. 198 and p. 222, 1908.

three or four days to values as low as 50 ohms, but he did not observe any light sensitiveness after the low resistance was reached.

THE CRYSTALLIZATION OF SELENIUM IN AN ATMOSPHERE IN WHICH MERCURY VAPOR IS PRESENT.

The first experiments that exhibited the action of mercury vapor on selenium were those in which the selenium in an ordinary cell form was crystallized in the presence of mercury vapor in air. The cell form consisted of two parallel wires wound around a porcelain cleat such as is used by the electrician for holding and insulating wires. The selenium was first melted on this cleat and then undercooled, thus giving the vitreous allotrope attached to the wires. This selenium form was then placed just over a heating bath of quartz sand. At the bottom of the sand was a globule of mercury. The bath was heated by a bunsen burner from below, and consequently the temperature of the mercury was much higher than that of the selenium. It was found that if the selenium was kept anywhere between 150° and 200° , its conductivity reached a very high value, which it maintained after cooling to room temperature. Immediately upon cooling the selenium displayed light-negative characteristics, *i. e.*, the conductivity decreased when the cell was illuminated.

It seems that the mercury diffused up through the sand and condensed on the selenium. As might be expected the higher the temperature of the sand bath and of the selenium, the sooner did the selenium reach an approximately constant high conductivity. If the selenium were kept at about 190° for about 10 minutes, the resistance of the cell would drop to about 20 ohms, while if the temperature were kept at 150° several hours were required in order that this conductivity might be attained. No differences in the light-characteristics could be detected by varying the temperatures within the range noted. However if the selenium were heated below 140° or above 200° , the light sensitiveness did not appear. Perhaps at the lower temperature an appreciable amount of the mercury vapor did not reach the selenium while at the higher temperatures an explanation must probably involve chemical union of the selenium and mercury or special allotrophic modification of the selenium. Some thirty samples were made in this way, with but the use of a single drop of mercury in the sand bath.

The characteristics of the light-negative selenium prepared in this manner were not investigated fully, but many of them behaved much like the specimen described by Miss Crum.¹ Aside from the light-

¹ PHYS. REV., 33, 538, 1911.

negative character, the irregularities and the lack of permanency were the most striking peculiarities. Frequently the resistance would take sudden jumps, particularly if the specimen was illuminated or jarred. Occasionally the selenium would be light-negative with faint illumination but light-positive with intense illumination, and even more frequently a specimen would temporarily change over from light-negative to light-positive character. At one time as many as one fourth of the samples in my possession were light-positive when tested with light of uniform intensity. Frequently the sensibility was quite great. One sample changed from 74.6 ohms in the dark to 104.0 ohms in the light. It maintained an average sensibility half as large for about a week. The irregularity of one sample is illustrated by the following readings taken with the selenium alternately in the dark and in the light, at intervals of about two minutes.

Resistance in Dark.	Resistance in Light.
100	117
100	101.5
98.8	105.0
95	

Not all the samples made in this way were permanent. The maximum change of resistance by light was probably greatest about two days after manufacture. After that time the sensibility gradually decreased until finally after a month there was almost no effect due to light action.

It was considered possible so far as the above experiment decides that the mercury vapor may have acted in any one of three ways. The mercury may have acted chemically on the selenium so as to form a selenide, it may have acted catalytically in a way to alter the equilibrium of the selenium components, or it may have been merely entrapped in the selenium, without otherwise essentially altering its electrical properties.

One basis for the belief in the formation of a selenide at this stage of the experimenting lay in the statement, in Watt's Dictionary of Chemistry, that mercuric selenide is formed when mercury and selenium are heated together. However I noted that mercury did not freely combine with selenium, even when the latter was heated to its melting point.

If the mercury were trapped in the selenium by some absorption process so as to form a kind of solid solution, we would at once have an explanation of the high conductivity that always accompanies this light-negative property. Perhaps the light action merely alters the form of the crystals in all varieties of selenium similarly, and in this light-negative variety it thereby breaks the conducting film of mercury. This is a simple and apparently satisfactory explanation. It readily accounts for the irreg-

ularity and non-uniform behavior of the new selenium form. However it does not explain why light-negative selenium should be produced in the presence of mercury vapor, under conditions that would not produce any light sensibility at all in the absence of mercury vapor.

Should the mercury vapor act catalytically, so as to alter the rates of change of the existent components in the selenium, we have at once a satisfactory explanation. The first difficulty in the way of this explanation is the possible formation of a selenide. More will be said later concerning these theories.

THE EFFECT OF UNHEATED MERCURY VAPOR ON LIGHT-POSITIVE SELENIUM.

There was considerable uncertainty in the last experiment as to whether the mercury vapor at the high temperature may not have acted on selenium by chemical union. If such chemical action did not take place then it seemed reasonable to hope that mercury vapor at room temperatures might transform light-positive selenium into light-negative selenium. This is particularly consistent with the view that in the light-negative selenium the conducting material is essentially mercury, which is broken and altered by the selenium crystals changing form under the action of light.

Accordingly two small cells, made by dividing a regular size Giltay cell into parts, were placed in an apparatus connecting with a Gaede vacuum pump. The resistance of each sample was upwards of twenty million ohms, in the dark, and possessed the usual sensibility to light. After being kept in a vacuum of less than .01 mm. for twenty minutes there was no apparent change in resistance, but after being in the vacuum for twelve hours the resistance had fallen to 40 ohms. At first the irregularity of behavior when illuminated resembled that of the light-negative samples previously described. The resistance was so unsteady that it was difficult to say just what action was due to the light. The cell was then placed in a kerosene bath. After resting thus for several hours, it showed consistent light-negative properties. The following is a sample of the observations taken with the selenium alternately in the dark and illuminated with a 16 c.p. lamp at 20 cm. distance.

Resistance in Dark.	Resistance in Light.
70.5	70.6
70.5	70.61
70.5	70.58
70.5	70.56
71.3	71.5

And after resting three months in the dark, the behavior is illustrated by these readings. The illumination was approximately that above.

Resistance in Dark.	Resistance in Light.
86.3	86.43
86.33	86.43
86.33	86.50
86.0	86.12
86.0	86.11

The curve in Fig. 1 shows the manner in which the resistance changes with the time of exposure. The rate of change is not nearly so rapid as that of a light-negative sample for which the curve is given in Fig. 9 of a former paper on the "Nature of Light-action in Selenium."¹

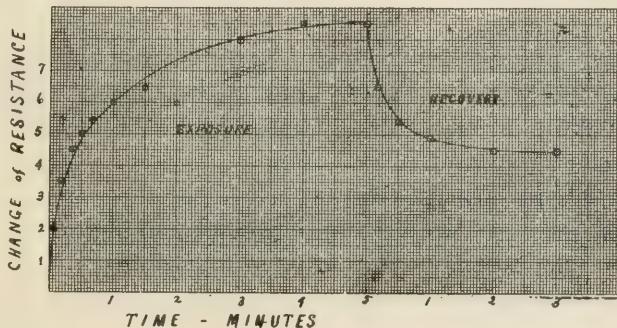


Fig. 1.

The difference in these two may be accounted for by the unequal light intensity in the two instances. At any rate the resistance begins to decrease at the instant of illumination in these new samples, and the change is so rapid at first that it is quite improbable that it is due to heat rather than light action. To definitely determine this point I hope soon to be able to map the sensibility of this variety of selenium throughout the spectrum, as Pfund² has done for light-positive selenium. Such a determination may also aid in a physical interpretation of the nature of the change of resistance.

The second sample referred to above was weighed before and after exposing it to the mercury vapor, to detect if possible the amount of mercury that was necessary to perform the observed transformation. Before placing in a vacuum and while the resistance was several million ohms the weight was 1.2527 gm. After exposing to mercury vapor in a partial vacuum for 16 hours, the resistance fell to 104 ohms. The

¹ PHYS. REV., 33, p. 19.² PHYS. REV., 34, p. 370, 1912.

weight had not changed by as much as 0.1 milligram. This result is not inconsistent with the supposition that the increase of conductivity arises solely from the direct conductance of the absorbed mercury vapor. For if it is assumed that the mercury vapor has the same conducting power as large masses of mercury, it can be readily calculated that a film of mercury 2.5×10^{-9} cm. thick would have been sufficient to account for the observed conductivity. Further the weight of such a film would be only 1.2×10^{-8} gm., which amount it would be impossible to detect by weighing. But even with this small amount of mercury inside the selenium the concentration of mercury would be about a billion times as dense as that in a saturated free space at the same temperature.

THE ACTION ON POWDERED RED AMORPHOUS SELENIUM.

If in the Giltay cell, we could have been certain that all the selenium was acted upon, we would have known by the absence of increased weight that no chemical action took place. But as there was no obvious change of color or appearance, no estimate could be made of the extent of action of the mercury vapor.

The red amorphous selenium was exposed to the mercury vapor in a vacuum with the hope that a change in color would indicate the extent of the action. First a very small fraction of a gram of the red powder was scattered in the vacuum tube. Within half an hour after high vacuum was reached this selenium had turned black. The selenium was then packed between two wire electrodes. The resistance was fairly steady at 240 ohms. It was also light-negative, showing an increase of from 0.5 to 20 ohms. After heating for thirty minutes at 210° the resistance was reduced to 1.2 ohms. For a week following this heating the resistance was unsteady and slowly increased in value. However it did become steady after this interval and it was then quite light-sensitive. Several light-negative samples were made by packing this black selenium between wire electrodes. They were all of very low resistance and light-negative in character.

The fact that the red amorphous form did change its color to a distinct black, made it seem apparent that chemical action did not take place. If mercury selenide were formed, then when all the selenium changed to the black form it should increase in weight by the ratio of 79 to 200.

TWO SAMPLES OF RED SELENIUM WERE WEIGHED AS FOLLOWS:

Test No. 1.

Weight of glass tube container	1.066 gm.
Container + selenium	1.661
In vacuum 4 hours, 90 per cent. black.	1.674
In vacuum 12 hours	1.667
In vacuum 10 hours longer	1.660

Test No. 2.

Weight of paper	0.514 gm.
Paper + red amorphous selenium.	.808
After 4 hours exposure to vapor ..	.803
After 12 hours longer exposure ..	.803
Exposure continued 6 hours808 selenium almost entirely black.
Exposure continued 4 hours797 mercury heated slightly.
Exposed to air 16 hours815
Exposed 10 hours longer in vacuum	.801
Exposed to air 3 hours813

A third test was made using 2.013 grams of selenium. After exposure for about 60 hours the selenium was mostly blackened, and the weight had increased to only 2.033 grams. During exposure the effect of the mercury vapor did not penetrate far into the mass of powder. It was seldom blackened deeper than a millimeter, so that it was necessary to frequently stir a fresh surface for exposure. The second test showed what seemed to be the hygroscopic property of the selenium, by an increase in weight when it was exposed to the air. The fact that the selenium is blackened only near the surface, leads to the belief that the absorbed moisture does not play a very important part in the transformation.

The figures in these three tests apparently demonstrate that chemical combination between the selenium and the mercury vapor is quite inconceivable. If there were any definite measurable increase of weight due to the absorption of mercury vapor, it is masked by the variations in weight due to moisture and uncertain causes.

However I was deceived here by assuming that because the selenium was blackened in from 4 to 60 hours, and increased in weight by less than .03 gram that there could be no further action between the mercury and the selenium. The truth is that while it was blackened it was not all acted upon. After being exposed 1,230 hours in a high vacuum a sample weighing 0.565 gram increased in weight to 1.803 grams. When the vacuum was kept at the X-ray stage the increase was almost uniformly one milligram per hour for the first 1,000 hours, but during the next 200 hours, the weight increased more and more slowly. If mercuric selenide were formed the weight should have ultimately increased to 1.995 grams. The fact that this weight was not quite reached can easily be explained by the loss of selenium during weighings and by diffusion of its vapor in high vacuum, if not to the fact that sufficient time was not allowed for complete penetration and action.

I do not believe it right to assume at this time that the mercury vapor in a finely divided state in the selenium can have these light-negative

properties, except for the action of light on selenium or the selenium compound.

One determination of the density of this new selenium gave 4.98, but this particular sample may have had some free mercury with it. With my arrangements it is a slow process to produce a sufficiently large quantity for an accurate determination of the density. A globule of mercury acts very rapidly on selenium surrounding it in a vacuum but at atmospheric pressure a mercury globule in contact with the red powder will not perceptibly color the selenium in several days. Later I hope to obtain the density more accurately. It will probably show the same density as mercuric selenide, which in fact it resembles.

It may be mentioned that powdered vitreous selenium when placed in an atmosphere of mercury vapor for 18 hours also assumes a high conductivity and the light-negative property. There is no apparent change in the color of this modification. It is rather strange that any powder should have such a high conductivity when rather loosely packed as the powders here were packed. The interaction between the mercury and the selenium arises probably more essentially from a property of the selenium. Powdered sulphur when exposed several days to mercury vapor at the same time the selenium was exposed showed no conductivity at all.

SUMMARY.

1. Mercury vapor acts on selenium in such a manner as to produce a very high conductivity and the light-negative property.
2. The mercury acts on the amorphous form and probably also on the other modifications so as to produce selenium of new characteristics. Permanent chemical compounds are probably formed between the mercury and the selenium.
3. A very easy and satisfactory method of making light-negative selenium cells is to place the amorphous selenium in a mercury vacuum until it becomes black, and then to press this black selenium between fixed electrodes.
4. The energy curve should be mapped out in order to gain evidence as to the similarity of action of light in this and light-positive selenium.

A PRACTICAL ELECTRICAL METHOD OF MEASURING THE
DISTANCE BETWEEN PARALLEL CONDUCTING PLANES,
WITH APPLICATION TO THE QUESTION OF THE
EXISTENCE OF ELECTRON ATMOSPHERES.

BY F. C. BROWN.

IN the Philosophical Magazine for August, 1912, Professor R. W. Wood raises the interesting question of the existence of conducting atmospheres surrounding metallic surfaces. The necessity for this hypothesis arose from a number of experiments, in which electrical conduction took place between metallic surfaces, when they were separated between 20 and 30 wave-lengths of sodium light. The hypothesis appeals to the imagination but it is not easy to reconcile it with the well-known experiments by Earhart,¹ Hobbs,² Kinsley,³ Almy,⁴ Williams,⁵ and others who found, by the use of interferometer methods, that there was good insulation when the conductors were much closer than the distances observed by Wood. Perhaps the argument may be urged against the interferometer methods that no allowance was made for a possible deformation of the metallic surfaces under the electrical stresses; nor have such methods as were used been infallible in detecting the absolute point of contact between the surfaces.

Moreover, Wood's experiments, considered alone, do not seem consistent with the electron atmosphere hypothesis, for such an atmosphere should extend out the same distance from the surface regardless of the insulating material between the surfaces, particularly so when the material is in discontinuous sheets. His results should not have shown a greater variation than the variation of his optical flat from that of a true plane.

I have tested an electrical method for measuring small distances in order to gain information which might help in explaining the above apparent discrepancies. I have found the method useful and the application interesting. The application can be most readily understood, after the method has been explained.

¹ Phil. Mag. (6), 1, p. 147, 1901.

² Phil. Mag. (6), 10, p. 617, 1905.

³ Phil. Mag. (6), 9, p. 692, 1905.

⁴ Phil. Mag. (6), 16, p. 456, 1908.

⁵ PHYS. REV., 31, p. 212, 1910.

The electrical method of measuring the distance between two plane conductors is based on a measurement of the electrical capacity which the two planes possess by virtue of their nearness. For small distances such as I used the distortion of the lines of force at the edge of the planes was so small that no appreciable error arose therefrom, and the capacity of the connecting wires and the upper plane isolated was only from three to five units and could be corrected for or neglected. This method involves the elementary but fundamental and absolute formula,

$$C = S/4\pi d, \quad (1)$$

where C is the electrical capacity of the two neighboring surfaces of area S , and d is the distance between the electrical charges on opposite planes.

Now if it should be revealed that the distance between the opposite electrical charges is the same as the distance between the mechanical surfaces, then obviously it should be concluded that within the accuracy of measurement the electrical and mechanical surfaces are identical. In other words the identity would establish that an electron atmosphere does not extend beyond the mechanical surface. The question as to whether both negative and positive atmospheres exist need not be considered at this time.

The capacity of two parallel plates can be measured readily to a satisfactory degree of precision by the method of mixtures. I used a Dolazalek electrometer of 20 E.S.U. capacity for the comparison capacity and also for measuring the necessary potentials. The procedure was first to charge up one pair of quadrants to a potential V_1 , represented by a deflection of the needle, D_1 . The quantity of electricity on the needle was then allowed to distribute itself between the electrometer of capacity C_e , and the parallel plates of capacity C . The resulting potential, V_2 , gave a deflection D_2 . As usual the capacity of the parallel surfaces is,

$$C = C_e \frac{(D_1 - D_2)}{D_2}. \quad (2)$$

Substituting the value of the capacity in equation (2), the distance between the conducting surfaces is obtained in the form

$$d = S \cdot D_2 / 4\pi C_e (D_1 - D_2). \quad (3)$$

Because of the low capacities to be compared this method requires a high degree of insulation for all the parts. I have been very much surprised to find how easy it is to obtain almost perfect insulation when the neighboring plates are separated by only a few wave-lengths of light. The

only precaution thus far found necessary is that the insulating material should be free from moisture and impurities. In general if material once dried is kept a few degrees above the atmospheric temperature, trouble due to moisture will be avoided. For very thin insulating material hours of heating may be required, so that it may insulate properly the conductors which it separates.

In these experiments I measured the distances between planes when the resistance was of the order of 10^{12} ohms, whereas Wood measured the distances when the conductivity could be measured by a galvanometer and a milli-ammeter. Naturally then I should have expected to work with planes separated farther than 20 or 30 wave-lengths, but I found in fact almost complete insulation at one or two wave-lengths, when the precautions mentioned were taken.

In 1908¹ I obtained insulating films which were only about 10^{-6} cm. thick. This is nearly a hundred times less than certain minimum insulating distances obtained by Wood. One of Wood's experiments indicated that a coating of oil did not interfere with the conductivity. So I tried first a film of turpentine. I evaporated a film of turpentine at high vacuum and allowed it to condense on a highly polished brass surface. After condensation I was able to bring up in vacuum a globule of mercury from below. The globule of mercury when earthed and brought up to the film altered the capacity of the electrometer system by the amount of the condenser formed. I was able to obtain by this method insulating distances of about 6×10^{-5} cm. As I was unable to measure the film thickness by a check method, it was not safe to conclude that the electron atmosphere did not extend into the turpentine.

The first experiments were made with conducting planes of hardened steel. They were made and polished by our instrument maker, Mr. M. H. Teeuwen, but the surfaces were not tested at the time optically for planeness, and the microscope showed them not to be free from scratches. However at the conclusion of all my experiments they were tested and found to vary from a plane by less than two wave-lengths. The area was about 1.8 sq. cm.

The two planes were separated by sulphur particles collected from an air suspension. Somewhat more than a thousand particles covered the surface of one of the plates, of which about 20 were larger than 0.007 cm. as seen by the microscope. When one of the plates was laid on the other there was complete insulation, *i. e.*, when the condenser was charged the potential did not vary noticeably in five minutes. The observations are shown in the following table.

¹ Phil. Mag. (6), 18, p. 649.

These results indicate that the electrical method gives a shorter distance than the diameter of the sulphur particles, but it was not certain

Approximate potential across sulphur particles, volts	4.34	3.4	1.8	0.6
Zero reading of electrometer, D_1	186	186	186	186
Reading of electrometer when charged, D_1	313, 329, 313	286, 289, 286	245, 247	205, 201, 201
Reading of electrometer when charges are mixed, D_2	225, 237, 234	225, 223, 226	205, 206	192, 193, 192
Capacity, E.S.U.	36	32	40	28
Mean distance	0.0044 cm.			

if the few largest sulphur particles might not crush or give or roll into the scratches under the pressure of the upper plate. Further it was not clear what action so many small particles would have on the dielectric constant of the intervening space.

Because the sulphur particles were not uniform in size and possibly not rigid, and because of the difficulty of getting rid of the moisture, I decided to try quartz fibers. A small fiber was broken into two parts and placed between the two surfaces. It was on a day in early May when the humidity was low, and the fibers were not previously heated, except in the oxygen flame when blown. Nevertheless the insulation was regarded as perfect. The following are the observations with these quartz threads separating.

Approximate potential between plates, volts	2	0.9
D_1	320, 319, 317	242, 245, 245, 244, 245
D_2	209, 208, 208	195.5, 196, 195, 197, 195
Capacity	100	103
Corrected capacity	97	100
Mean distance00151 cm.	

Now the size of the quartz fibers separating the planes as determined by the micrometer eyepiece on the microscope was

$$.00165 \pm .000086 \text{ cm.}$$

This difference by the two methods between the distances then varies by only about two wave-lengths. I found later in reading the size of fine fibers by the microscope, that it was much easier to err by obtaining values too large than too small. This experiment then leads to the con-

clusion that if there be a conducting atmosphere, it must not extend out more than two wave-lengths.

Obviously the conclusion just arrived at is inconsistent with Professor Wood's suggested interpretation of his experiment, in which he obtained a current of several milli-amperes when parallel planes were only five wave-lengths apart. I therefore thought it advisable to repeat the experiment using smaller quartz fibers, this time three in number. The sizes were:

First.....	.00052 cm.
Second.....	.00053
Third.....	.00059

And the mean probable distance of separation was therefore .00056 cm. The electrical method by the mean of five observations, with 0.3 volt across condenser, gave a separating distance of .00054 cm.

There are two conclusions that should be drawn from this experiment. First, there was almost perfect insulation when the two planes were separated by only ten wave-lengths, and, second, conducting atmospheres could not have extended as much as two wave-lengths outside the mechanical surface.

A further attempt to repeat the above experiments with yet finer quartz fibers met with failure owing to unsatisfactory insulation. I did not try heating the quartz fibers at this time because I feared that the steel surfaces might vary by ten wave-lengths. I observed that it was impossible by the electrical method to obtain insulation at distances less than those measured by the microscope. Unless some unknown factor is involved, this observation obviously leads to a third conclusion, which is that conduction at short distances arises from conducting material and not from an electron atmosphere of unvarying depth.

The question as to the imperfect insulation at less than 9 wave-lengths was still unanswered. Possibly the insulating properties of certain dielectrics break down when a certain minimum thinness is reached. It was thought that a constant minimum thinness for any given material would strengthen this view. Or perhaps as Wood suggested films of moisture about small particles might readily explain the imperfect insulation if not also the high conduction. We shall recur to this point in a succeeding paragraph. But the most opportune explanation, whose plausibility should be considered, was the possible irregularity of the steel surfaces.

The question of the planeness was answered in two ways. First, a glass plate with plane sides was moved over the surface of the plates

and the character of the interference fringes noted. By this test the extreme variation of the surface was not as much as two wave-lengths.

Second, two optical flats on speculum metal were obtained, whose surfaces by optical test did not vary from a plane as much as one wave-length. With these my surprise was certainly great when I found imperfect insulation when the surfaces were separated by quartz fibers of 24 wave-lengths diameter. As my supply of quartz fibers, and also of oxygen was exhausted, I now turned to the use of mica flakes for insulation material. At first when a continuous sheet of mica of 25 wave-lengths separated the flats the insulation was imperfect. If charged to a potential of 4 volts, three fourths of the charge would leak off in 10 seconds, but by thoroughly heating the plates and the mica over an electric oven the insulation became quite perfect. This was more than a month after my experiments with the iron surfaces, and I now found it quite impossible to obtain good insulation without heating the plates and the insulator. Presumably the excess of humidity was the cause of the trouble.

In one instance the speculum surfaces were separated by three mica flakes of a total area of about 5 mm.^2 . By the microscope one was about 14 wave-lengths, the second 12, in thickness. The third was not measured. When the electrometer was charged to + 5 volts and mixed with the speculum condenser the capacity was 310 cm., and when it was charged to - 5 volts the capacity was 315 cm. The total pressure on the upper plate was about 50 gm. From this capacity was subtracted 59 units as a correction for the added capacity due to the mica flakes and to the plate aside from its condenser action. The area of the plates was 1.84 cm.^2 . The distance between the surfaces was therefore calculated to be .00060 cm. It seems safe to conclude from this experiment that the difference between the electrical and optical methods is not more than three wave-lengths.

It was observed that if the pressure on the plates was increased to 100 gm. the insulation became very poor. Sometimes the insulation would be restored by removal of the pressure and sometimes not. However increased pressure did not always alter or destroy the insulation.

Again three very thin mica flakes were selected. By direct reflection they all appeared a brilliant green, but when viewed by the light that struck at a very large angle of incidence some of them appeared orange colored. With these flakes between the flats the speculum plates slid over each other freely as if nothing was between, and likewise they resisted pulling apart. The electrical resistance between the plates was very low, although I did not measure it. Continued heating with the two plates

together did not restore the insulation, although the mica had been heated for hours before the flakes were separated off the sheet mica.

Then the plates were separated and heated for two hours over an electric oven. The temperature of the plates was kept at about 215° . The mica flakes stuck tight to the plates during this procedure, although some of them did break in pieces. By this the insulation was made almost satisfactory, as may be seen from the following observations. It was necessary to determine the deflection from the first few swings of the needle. The period of the electrometer needle was about 10 sec.

	Pressure 90 gm.				30 gm.			
	0	0	0	0	00	0	0	0
Zero.....	0	0	0	0	00	0	0	0
D_1	+33	+33	-43	-43	-82	-83	-80	-80
D_2	1	1.5	-2	-1.5	-3.5	-3.5	-3.6	-4.0 after 10 sec. -3.2 after 20 sec. -2.2 after 30 sec.
Mean of D_2		1.5						
Mean.....								3.65
Corrected mean.....								4.45
Distance.....					.00031 cm.		.00043 cm.	

Since heating the mica and plates to 215° had made the insulation so nearly satisfactory, it seemed wise to repeat this treatment. The plates were kept covered with Japanese silk tissue to prevent dust particles from settling on them. After six hours the plates were removed while hot and tested at once. The insulation was not perfect but it was improved and at the same time the capacity was larger. At the beginning of the test the natural leak was such that the electrometer needle went from 3 div. to 1 div. in 50 sec. At the end of the observations the natural leak was from 2.7 to 1 in 20 seconds, from 1.0 to .5 in 30 sec., showing that the insulation deteriorated with time, possibly owing to the formation of a film of moisture as the plates cooled. The natural leak was corrected for in calculating the distance. The observations shown in table on page 321 were obtained before the insulation deteriorated seriously. I was not able by the microscopic method to determine the thickness of the mica flakes, further than to limit their probable size to less than five wave-lengths. This much also was determined by a micrometer screw gauge. Then interference fringes were formed by bringing two optical flats on glass into contact along one edge and allowing the opposite edges to be separated by the mica flake. The number of fringes between the point of contact and the mica obviously gives twice the thickness of the mica in wave-lengths. The great difficulty in this measurement was that sometimes considerable pressure had to be applied in order to bring the

Zero.....	0	0	0	0	0	0
D_1	32	32	32	-81	-81	-82
D_2 , 10 sec.....	.25	.5	.5	-1.0	-1.25	-1.3
20 sec.....				- .5	-1.25	-1.0
					Mean.	
Zero.....	0	0	0	0	0	
D_1	-82	-82	+83	+83	-82	
D_2 , 10 sec.....	-1.25	-1.0	+1.0	+.8	-1.25	1.1±.14
20 sec.....	-1.0	-.85		+.4	-1.0	
Mean corrected.....				1.4		
Capacity.....				1,170		
Distance, cm.....				.00013		

plates into contact at one edge, much greater than was applied to the speculum metal plates. There was considerable irregularity in the pressure required to cause contact, and it may have been that, after heating, the speculum metal plates were separated only by the thickness of the mica. At any rate one of the mica flakes measured in this way had a thickness of two and a half wave-lengths, another one of two, and a third one of only one wave-length.

I observed after the second heating that the mica flakes on speculum surfaces showed the same deep green color that they exhibited when free. This rather indicates close contact between the mica and the speculum. Also the fact that long-continued heating permitted the electrical charges to come closer together, when separated by mica, indicates that heating either drives off something that conducts and separates, or alters the structure of the surfaces. If the mica flakes were in contact with the speculum, then there can be no conducting atmosphere of more than two wave-lengths of light, for this I regard as about the safe limit of accuracy of my experiments, but if on the other hand there exists a conducting atmosphere which is at the same time a mechanically separating medium, then it would not be safe to set such a low limit on the thickness of a possible electron atmosphere. The question will not be definitely settled until the distances are measured simultaneously by the two methods. We propose to do this by using very thin films of platinum deposited on plane glass surfaces. It is hoped thereby to finally decide to a fraction of a wave-length whether or not an electron atmosphere exists, and also to obtain information on the rôle played by insulating materials of small dimensions.

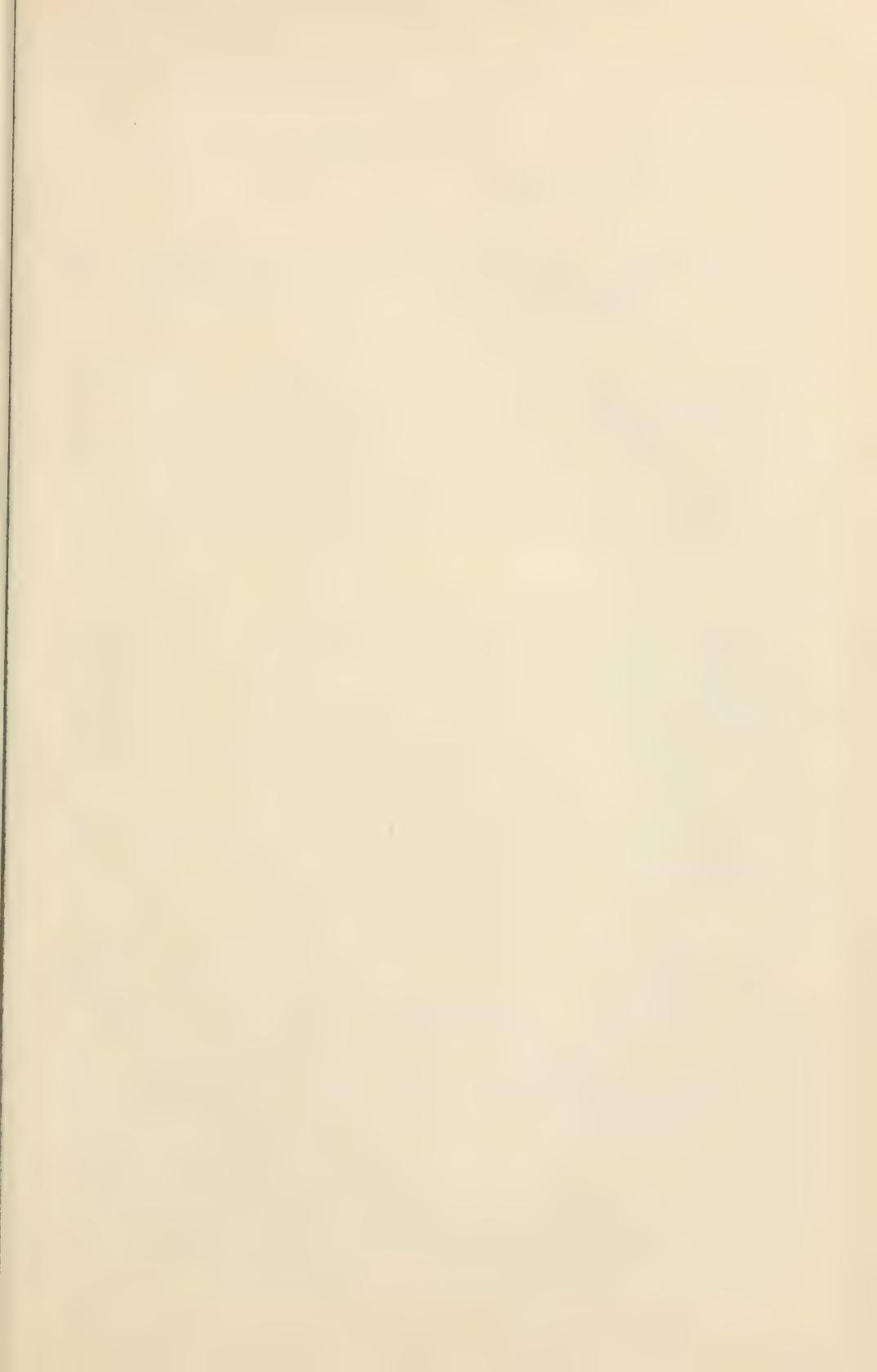
In as much as heating certain insulators such as mica and quartz restored their insulating properties, it is certain that the conduction obtained by Wood at such long distances was due to the presence of

the insulating material, and it is presumed that films of moisture and conducting particles were responsible for it.

In conclusion it may be said that while the electrical method was satisfactory as here used, it can be more accurately adapted to the problem in hand by more suitably choosing the suspension for the electrometer needle and by using a larger capacity in parallel with the electrometer.

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THE CHANGE IN THE ELASTICITY OF A COPPER WIRE WITH CURRENT AND EXTERNAL HEATING.

By H. L. DODGE.

THE present investigation consists of determinations of Young's modulus of a specimen of copper wire at various temperatures between 20° C. and 150° C. with the object of ascertaining whether or not heating by an electric current has any effect other than that caused by the accompanying increase of temperature, and also to learn certain facts regarding the temperature effect itself, concerning which there seems to be considerable doubt.

PREVIOUS RESULTS UPON THE EFFECT OF CURRENT HEATING.

Wertheim¹ reported a decrease in Young's modulus caused by current and believed this decrease to be independent of any temperature effect, a conclusion not sufficiently justified as he assumed the heating effect of the current negligible. Edlund² made allowance for the temperature effect, and concluded that current, except for the accompanying temperature change, does not affect Young's modulus. Streintz³ made observations of the torsion modulus at room temperature and at 55.5° C. The following figures represent the percentage change of elasticity caused by the current, correction being made for the temperature effect: Brass (a), - 5.9; (b), + 12.8; copper, 0.0; silver, + 3.9; iron, + 3.1; steel, - 12.2. Mebius⁴ found the effect due to current in the case of steel, iron, brass, and silver rods to be extremely small. Miss Noyes⁵ studied steel, silver, and copper wires and found that the current heating caused a uniform decrease in Young's modulus which could be entirely accounted for as a temperature effect. Walker⁶ employed the same experimental methods as Miss Noyes, but found very irregular changes with steel, soft iron, platinum, and copper, which could not be accounted for by temperature and which differed greatly with increasing and decreasing

¹ Ann. de Chim. et de Phys., 12, 610, 1844.

² Annal. d. Phys., 129, 15, 1866; 131, 337, 1867.

³ Annal. d. Phys., 150, 368, 1873.

⁴ Oefvers. af k. Vet. Akad. Forhandl., 681, 1887; Beibl. 12, 678.

⁵ PHYS. REV., 2, 279, 1895; 3, 433, 1896.

⁶ Proc. Roy. Soc. Edin., 27, 343, 1907.

current. A survey of previous work leaves a serious doubt as to the effect of current heating, and this doubt a critical study serves to increase.

PREVIOUS RESULTS UPON THE CHANGE OF YOUNG'S MODULUS WITH TEMPERATURE.

The investigations that have been carried on to determine the change of Young's modulus with temperature are so extensive that the results with copper only can be considered. These are however representative of the results for other metals. Shakespeare¹ has found a decrease of Young's modulus for copper of 3.6 per cent. on heating from 13° C. to 100° C. Miss Noyes² made observations at various temperatures up to 150° C. and reports a uniform decrease of the modulus of 0.13 per cent. and 0.07 per cent. per degree for two samples of wire. Gray, Blyth, and Dunlop³ also were able to make observations at intermediate temperatures up to 100° C. They also report a uniform decrease, which for two samples was 0.015 per cent. and 0.04 per cent. per degree respectively. On the other hand Slotte's⁴ observations at intervals over a range of 10° C. to 70° C. upon two samples of copper wire showed a decrease of Young's modulus with increase of temperature which was not uniform but became less rapid with one sample and more rapid with the other as the temperature increased. An increasing rate of change is also indicated by the results of Wertheim⁵ at 15° C., 100° C., and at 200° C., the change being much greater for the upper interval. In this connection the work of Pisati,⁶ Kohlrausch and Loomis,⁷ and of Slotte⁸ upon the torsion modulus is of interest. They found the rate of decrease of the modulus greater as the temperature was raised. This is suggestive as it is highly probable that the general nature of the elastic changes is similar for the two moduli. These results leave no doubt that increase of temperature causes a decrease of Young's modulus, but there is no conclusive evidence as to the exact nature of the decrease.

SCOPE OF WORK.

In view of the facts which have been cited it was decided to attempt an investigation of the effect of current upon Young's modulus, accompanied by a parallel investigation of the temperature change produced by an

¹ *Phil. Mag.*, 47, 539, 1899.

² *Loc. cit.*

³ *Proc. Roy. Soc.*, 67, 180, 1900.

⁴ *Acta Soc. Scien. Fennicae*, Vol. 26, 1899.

⁵ *Loc. cit.*

⁶ *Nuovo Cimento*, 4, 152, 1878; 5, 34, 135, 1879.

⁷ *Annal. d. Phys.*, 141, 481, 1871.

⁸ *Acta Soc. Scien. Fennicae*, Vol. 35, 1908.

external source of heat. Examination of the previous work led me to believe that the desideratum was not a hastily made series of observations upon a number of metals but rather thorough and extended observations upon a single metal. Consequently this report is confined to results with copper although work is under way with other metals. A review of the literature made clear that the causes of inaccurate results in the past have been chiefly a lack of mechanical perfection in the apparatus and insufficient attention to the distribution of temperature. In none of the work upon the effect of current has there been any knowledge of the differences in temperature along the wire or any effective attempt made to secure a uniform distribution. The apparent crudity of the apparatus that is here described is the result of an attempt to keep every part of the apparatus as simple as possible and to refrain from unwarranted refinements. Each source of error has been considered in relation to the others and the effectiveness of the apparatus is best judged from the consistency of the results that have been obtained.

DESCRIPTION OF THE APPARATUS.

In order to prevent convection currents and consequent non-uniformity of heating necessarily accompanying vertical suspension the wire was mounted horizontally. The mechanical features of the apparatus (Fig. 1) may be considered independently of the heating box. The wire is

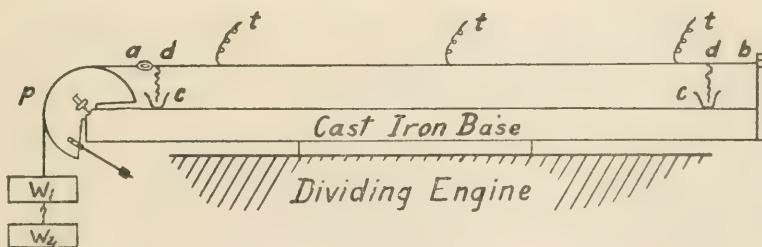


Fig. 1.

The apparatus, showing method of suspending the test specimen.

suspended between a bar (*b*) and a pulley (*p*) which are in turn supported by a heavy cast iron base, bolted to the carriage of the dividing engine. The wire is stretched by the weights W_1 and W_2 . Current is led in at the points (*d*) through the mercury cups (*c*), the wire being insulated at (*a*) and at (*b*). Three copper-constantan thermo-couples (*t*) of No. 36 wire are for temperature measurements. The weight W_1 is kept upon the wire continually and is heavy enough to stretch the wire almost straight. The weight W_2 is added gradually and without jar by a simple

apparatus operated by a foot lever. The elongation of the wire is measured with two micrometer microscopes attached to the bed of the dividing engine. These are focused upon bright scratches on the wire, made visible by incandescent lamps.

The heating apparatus (Fig. 2), although supported by the cast-iron base, is mechanically entirely independent of the wire. It must not only furnish a means of heating the wire externally but also must retain the heat when the current is passed through the wire itself. The base (*o*), bottom piece (*s*), and back (*v*) are covered with asbestos and fastened together. The asbestos-covered front (*h*), which has two windows of mica (*m*) for observing the wire, and the glass cover (*n*) are held together by clamps easily removed. The glass tubes (*k*) are large enough to give sufficient clearance to the wire (*w*) but small enough to prevent convection or other air currents. Zigzagging back and forth across the bottom piece (*s*) is a heating wire of German silver through which a current can be

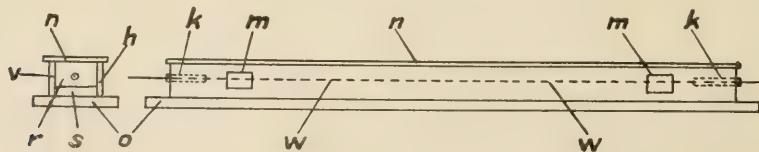


Fig. 2.
Heating box surrounding the test specimen.

sent. This heating box proved to be one of the three important features of the apparatus and its simple form in no way indicates the difficulty of securing a reasonably even temperature distribution. This fact is very suggestive in connection with the results of former investigations in which average temperature only was known, there being no information concerning the temperature distribution. The use of thermo-couples which could be slipped to different portions of the wire revealed surprising inequalities of temperature. Even after uniformity of heating had been secured with the external source it was necessary to still further alter the box before a satisfactory distribution could be obtained with internal or current heating. At the highest temperature employed the maximum variation of temperature over the portion of the wire under observation was less than 15° C.

A second feature of importance is the free suspension of the wire. The possibility of error due to contact of the wire with rigid portions of the apparatus is eliminated by permitting it to touch nothing except the thermo-couples which are of fine flexible wire. Consequently the specimen hangs freely in the form of a flat catenary. The elongation

caused by the straightening of the catenary on the application of the additional stretching weight is negligible, being about $1/100$ of the smallest reading of the micrometer microscope. The third feature is also mechanical. It is the pulley which changes the direction of the applied force, which must be transmitted without gain or loss resulting from friction or change of leverage. Fig. 3 shows its construction and suggests the method of centering the axis. The pulley was tested at different posi-

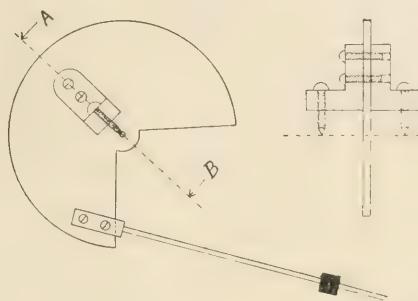


Fig. 3.
Side view of pulley and section along A-B.

tions at various times during the progress of the work and found to introduce no appreciable error.

METHOD OF DETERMINING TEMPERATURE OF SPECIMEN.

When the wire is heated by the external source it is of uniform temperature throughout its cross section and of the same temperature as the surrounding air. Under these conditions the thermo-couples which have already been mentioned are a perfectly satisfactory means of measuring its temperature. In the case of internal or current heating there is an increase of temperature toward the center, resulting in a number of effects, change of resistance, thermal conductivity, etc., each of which has its influence upon the current distribution and in turn upon the temperature distribution. The average temperature of the wire is of course a function of the surface temperature and of the current, but for evident reasons the thermo-couples do not give the surface temperature of the wire when the wire itself is the source of heat.

Measurement of temperature by change of length caused by thermal expansion has proved to be the most accurate and convenient method. Blondlot¹ has shown conclusively for several pieces of brass and one of German silver that current has no direct effect upon the dimensions of

¹ Journal de Phys., [1], 8, 122, 1879.

a metal carrying a current. This has also been shown by Righi¹ for four wires whose composition is not given. There is no reason to believe that copper should be peculiar in showing this effect. In fact our own experience and the persistency with which our results for Young's modulus at any temperature as determined by this method remain the same, no matter what may be the source of heat, is in itself proof that current has no direct effect upon the length of the wire. In using change of length as an indication of temperature account must be taken of the change caused indirectly by the effect of temperature upon Young's modulus. Thermo-couple readings and length observations were taken for all work with external heating. With internal heating length observations were made and the temperature determined by comparison with the other results. The thermo-couples were connected to a sensitive Siemens and Halske galvanometer by a three-way switch and were calibrated by direct comparison with an accurate thermometer.

With current heating the central portions of the wire tend to lengthen more than the outer portions which are at a lower temperature and it is assumed that the actual lengthening so averages this effect as to be an indication of the average temperature. It is also worthy of notice that the contribution to Young's modulus will be different for the different portions, the value observed being an average of the moduli of the various circular layers making up the cross section of the wire. There is of course a similar averaging of temperature and modulus along the length of the wire.

NATURE OF THE TESTS.

Three sections of commercial copper wire were tested, all from the same piece obtained from the Driver-Harris Wire Co., Harrison, N. J. The purity of the specimen was determined electrolytically, with results of 99.88 per cent. and 99.92 per cent. As the second was the more accurate we may take $99.91 \pm .01$ as the purity of the specimen. There was no trace of either silver, lead, or iron. The coefficient of linear expansion was .0000169. Specimen No. 2 was 0.81 mm. in diameter. The portion under observation was 50.7 cm. long. The other samples were of similar dimensions. A weight of 2,109 grams was kept upon the wires continually. The modulus was determined by measuring the elongation produced by an additional weight of 2,252 grams. The elongation was observed with a microscope, the micrometer head of which can be read to 1/50 revolution, corresponding to .00093 mm. stretch. At room temperature the stretch amounted to about .02 mm.

¹ *Nuovo Cimento*, [3], 7, 116, 1880.

Currents as high as 15 amperes were used. The accuracy of the work is of a high degree. The error in the determination of Young's modulus is about 1 per cent. A greater accuracy may prove desirable if small peculiar effects appear with other metals, but the present apparatus is sufficiently accurate to determine the general nature of the changes in the modulus.

Each determination of Young's modulus as represented by a point on the curves or a value in the tables is the result of ten or more separate measurements taken so as to eliminate any error caused by a slight drift in temperature. Generally a half hour or more was required for the temperature to reach a sufficiently steady state. After the preliminary work the greater part of the observations consisted of series of determinations with increasing or decreasing temperature over a range of 20° C. to 150° C.

PRELIMINARY TESTS.

The possible ways in which current may affect elasticity are so numerous that a determination of Young's modulus at a given temperature is of no value unless interpreted in connection with the whole thermal history of the wire. Since the essential part of this investigation is the comparison of observations taken under as nearly similar thermal conditions as possible, except for the difference in time and in the source of heat, an elimination as far as possible of any other than pure temperature effects is desirable. If this is impossible a thorough understanding of the nature of the other effects is essential. In order to eliminate the well-known permanent changes accompanying extreme temperatures the treatment of the wire after its first heating and stretching was confined to a temperature range of 20° C. to 150° C. In order to find out how consistent was its behavior within this range and under the various conditions of treatment a great deal of preliminary work was necessary. This showed that there are no sudden changes in the elastic state of the wire, that the rapidity of heating and cooling had little if any effect upon the changes in elasticity, and that the length of time the wire was held at a given temperature had no great effect. As explained later, permanent or history effects were found, but for any series of readings these changes were insignificant, the value of Young's modulus returning at the close of any day's observations to practically its original value.

That history effects could be eliminated and the elasticity of the wire made independent of treatment and a function of temperature only is illustrated in Fig. 4, Series 5. Observation 15 is almost identical with 8, and 16 and 17 are nearly the same as the first observations, although the wire had meantime been heated and cooled twice.

In order to learn whether or not at any given temperature the value of Young's modulus is dependent upon the manner of heating, the observations of Table I. were made. The shifting from one method of heating to another was done without permitting much alteration in the temperature of the wire.

TABLE I.

Showing Constancy of Young's Modulus under Different Conditions of Heating, Temperature Remaining the Same.

Method of Heating.	Variation in Length, Mm.	Variation in Stretch, Mm.
12.8 amperes, alternating current.....	.0000	.0000
12.8 amperes, direct current.....	.0065	.0009
External, direct current.....	.0059	.0009
External, alternating current.....	.0032	.0014
12.2 amperes, direct current.....	.0018	.0009

The greatest variation in length is .0065 mm. or 0.14 revolution of the micrometer head. This corresponds to a temperature variation of less than one degree Centigrade. The greatest variation in stretch is .0014 mm. This corresponds to only 0.03 revolution and is about the experimental error. These results show clearly that at this temperature, which was approximately 110° C., the stretch modulus is independent of the source of heat. These preliminary investigations and others which need not be described showed the behavior of copper to be very consistent and are the justification for the taking of more extended series of observations and the comparison of results secured at different times.

TESTS UPON SPECIMEN No. 2.

After specimen No. 2 was placed in the apparatus it was heated to a high temperature and stretched to remove the kinks. Afterward it was never heated above 150° C. The four series of readings composing Fig. 4 were taken after the wire had been heated by both methods a total of about 50 hours and after about 500 applications of the stretching weight. If such a thing were possible as a state in which all changes in elasticity, except those caused by temperature could be eliminated, this treatment should have secured the result.

As far as possible the figures have been made self-explanatory. Certain additional information which is characteristic of all the work is given in Tables II. and III. Series 4 shows a series of observations in which the heating was entirely external. In this as well as in the other three series of Fig. 4 dotted points represent observations taken while the

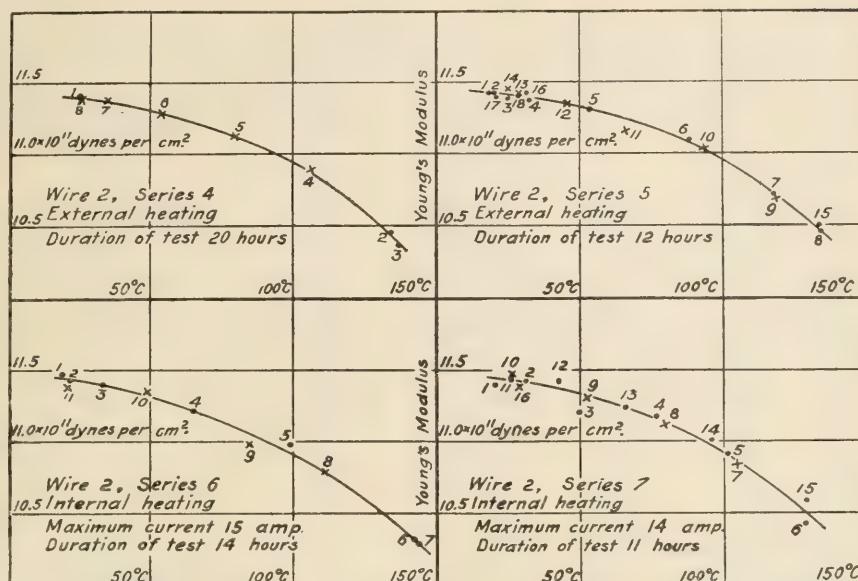


Fig. 4.

Results of tests upon specimen No. 2, showing effect of internal and external heating.

TABLE II.

Data for Series 5, Wire 2, External Heating.

Obs. No.	Time.	Temp.	Stretch (Revs. of Micr. Screw).	Young's Modulus $\times 10^{11}$ Dynes per cm^2 .
1	9:00 A.M.	18° C.	4.08	11.46
2	9:30	20	4.08	11.46
3	10:05	25	4.10	11.42
4	10:30	33	4.11	11.40
5	11:05	54	4.13	11.33
6	11:50	88	4.205	11.11
7	1:00 P.M.	118	4.35	10.73
8	2:00	135	4.47	10.48
9	2:45	119	4.365	10.70
10	3:15	94	4.24	11.05
11	4:10	67	4.19	11.18
12	4:40	46	4.12	11.38
13		28	4.09	11.44
14	6:00	25	4.075	11.48
15	7:15	134	4.45	10.52
16	8:00	32	4.085	11.45
17	8:45	21	4.10	11.42
18	9:30	28	4.09	11.44

TABLE III.

Data for Series 7, Wire 2, Internal Heating.

Obs. No.	Time.	Temp.	Current, Amperes.	Stretch (Revs. of Micr. Screw).	Young's Modulus $\times 10^{-11}$ Dynes per Cm ² .
1	10:30 P.M.	21° C.	0.0	4.10	11.42
2	11:15 A.M.	32	3.8	4.085	11.45
3	11:50	50	7.0	4.165	11.22
4	1:05 P.M.	77	9.8	4.18	11.20
5	1:30	102	12.0	4.28	10.93
6	2:30	128	14.1	4.49	10.43
7	3:05	105	11.9	4.31	10.85
8	3:50	80	9.5	4.20	11.13
9	4:20	53	6.8	4.13	11.33
10	5:10	27	0.0	4.07	11.50
11	6:30	27	0.0	4.08	11.46
12	7:25	43	5.0	4.09	11.44
13	8:00	66	8.0	4.15	11.26
14	8:45	97	11.2	4.245	11.02
15	9:15	129	13.9	4.42	10.60
16	9:40	28	0.0	4.10	11.42

temperature was being raised by steps and the crossed points those when the temperature was being lowered. Particular attention is called to points 2 and 3, the second of which was taken after the temperature had been maintained for twelve hours. They show that the length of time the wire was kept at the high temperature had no effect upon its elasticity. The proximity of points 8 and 1 shows the elimination of history effects and permanent changes.

Two days later Series 5 was secured, which yields results identical with those of Series 4, showing that the work of one day can be repeated at a later time. Further proof of the absence of history effects is afforded by the positions of points 14, 15, 16, 17, and 18 relative to observations taken at earlier times at the same temperatures. The fact that points 5, 6, and 7 taken with increasing temperature fall on the same curve as points 9, 10, and 12 taken with decreasing temperature shows the absence of any hysteresis effects.

Series 6 was taken three days later, followed the next day by Series 7. The procedure was the same as before except for the difference in the manner of heating. In Series 4 and 5 the wire was heated externally by means of the heating wire on the bottom of the box enclosing it. In Series 6 and 7 the wire was heated by an electric current in the wire itself. The results of Series 6 and 7 show the absence of hysteresis effects and the elimination of history effects the same as with external heating. The fact that the variation of the curves forming Fig. 4 is less than would

be expected from the experimental error shows that one is justified in taking these results as an indication of temperature effect alone and is justified in comparing the results of different days with different methods of heating.

TESTS UPON SPECIMEN No. 3.

A third sample of the same wire was next placed in the apparatus in order to confirm the results obtained with the former specimen, to attempt still other variations in the thermal treatment and to secure the complete elastic history of a specimen. The results are given in Figs. 5, 6, and 7. Upon these curves appear every observation that was made with the third specimen, not one having been discarded.

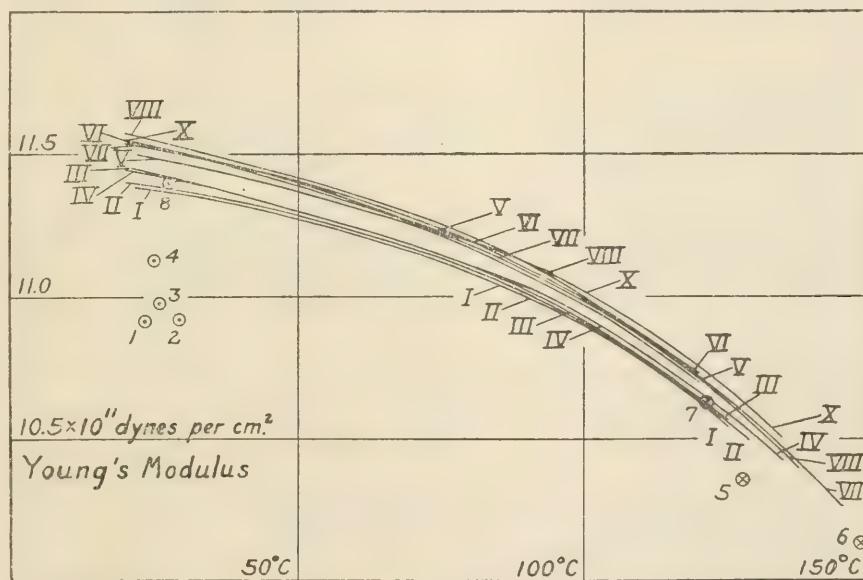


Fig. 5.

Complete elastic history of specimen No. 3. The curves are those of Figs. 6 and 7, the Roman numerals corresponding to the series numbers.

First Changes in Elasticity.—The specimen was made as free from kinks as possible and placed in the apparatus. Observation 1, Fig. 5, was at room temperature. The wire was then heated externally to about 125° C. and cooled. Observation 2 shows no change. Heating by 17 amperes current to about the same temperature brought a slight increase in the modulus as indicated by observation 3. There was very little increase in length during this treatment, as the additional weight was not applied at high temperatures.

It was anticipated that continued application of the additional weight while the wire was hot would remove any kinks in the wire, cause an increase in length and a change in the modulus. The wire was heated on by 17 amperes current and the weight applied a number of times. On

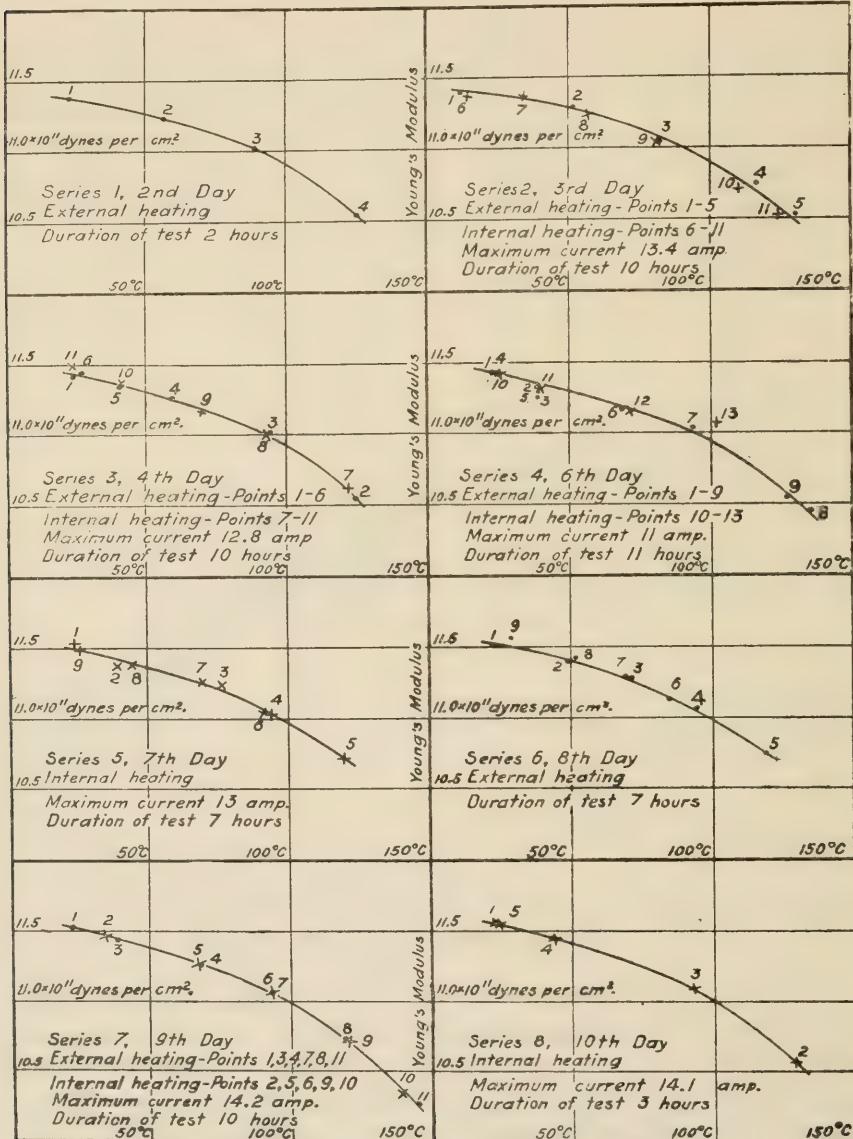


Fig. 6.

Results of tests upon specimen No. 3 with different thermal treatment, showing history effect, change of Young's modulus with temperature, and absence of any effect peculiar to current heating.

cooling an increase of length of about 0.2 mm. was found and an increase of Young's modulus as indicated by observation 4. The wire was again heated to 125° C. and Young's modulus measured at this temperature, resulting in observation 5. The temperature was then increased to about 150° C. and the additional weight applied about thirty times, resulting in observation 6. Cooling to 122° C. gave observation 7, and to 28° C., observation 8. It was believed that a sufficiently steady state had been secured to justify the trial of a series of readings and a comparison of points 6, 7, and 8 with reference to later observations shows this to have been the case. It is highly probable that the increase in Young's modulus due to this particular treatment was caused as much by the mechanical stretching and straightening of the wire as by the thermal treatment, although the latter was undoubtedly essential to the securing of the steady state.

Discussion of Fig. 6.—Following the work just described came eight days of testing under a variety of conditions. Fig. 6 shows the results and has been made practically self explanatory. The order in which the observations at the different temperatures were taken and the manner of heating were varied in a number of ways in order to catch any possible changes caused by treatment. Series 1 is with external heating, increasing temperature. Series 2, first part, was taken in exactly the same manner and the results show that for external heating a sufficiently steady state had been reached so that only small permanent changes were to be anticipated. The second part of Series 2 was taken in exactly the same manner except for the change in the manner of heating, the external heating having been changed to internal by means of the current. No difference is observed. The following day a series was taken in a similar way except that the observations were made with decreasing temperature. The nature of the temperature change remains the same and a slight permanent increase appears.

In Series 4 the systematic heating and cooling over the whole temperature range was not followed, but no peculiar effects were observed. During the following night the wire lay unstretched and it is possible that this had some influence in causing the permanent increase of elasticity observed the next day. Series 5 is the result of heating and cooling with internal heating and Series 6 is for the same treatment with external heating. No hysteresis effect appears nor does there appear any difference due to method of heating.

Discussion of Series 7.—Series 7 is the most interesting single set of observations, and was taken in order to compare the two methods of heating without permitting the elapse of several hours or allowing an

appreciable change of temperature. At each temperature at which observations were taken, the change in heating was made gradually, without permitting the temperature of the wire to change. Observation 1 was at room temperature. Observation 2 was with current heating. Without permitting more than a few degrees variation in temperature the current in the wire was decreased while that in the heater was increased. Observation 3 was with external heating. The temperature was then increased and observation 4 taken. Again the method of heating was gradually changed until observation 5 was secured with internal heating at practically the same temperature. In the same way 6 and 7; 8 and 9; 10 and 11 were taken. The results show in a striking manner that the changes accompanying current heating are only temperature effects. The tests of the tenth day with internal heating gave Series 8.

In any single series of this group the permanent changes with treatment do not appear prominent. But a comparison of the eight curves, Fig. 5, reveals a gradual increase of Young's modulus from day to day. This was caused undoubtedly by the continued application of the additional weight which caused a very small gradual stretching.

Effect of the Period of Rest.—Two days after the observations of Series 8 a measurement was taken at room temperature after which the wire was undisturbed for 106 days. This last observation appears with Series 9, Fig. 7, and a comparison with point 1 shows a slight recovery of

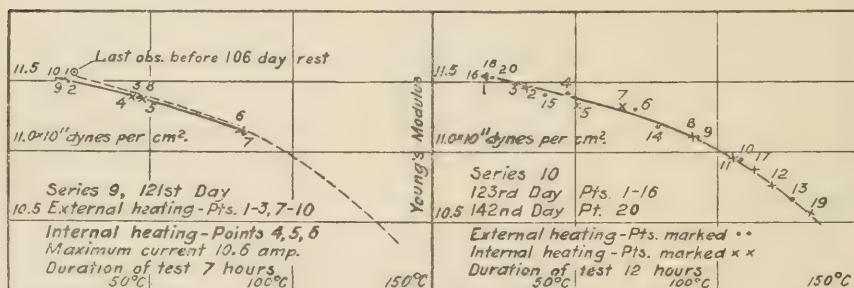


Fig. 7.

Results of tests upon specimen No. 3 after 106-day rest.

the wire during the long rest. Nine other observations were then taken with an idea of determining whether or not the modulus would remain low upon heating. This proved to be the case both for external and current heating as is clearly brought out by comparison with the dotted line which is the Series 8 curve. Two days later, as shown by Series 10, further heating and testing brought the specimen back to its former state

for low temperatures although at high temperatures greater values of Young's modulus were observed than ever before. Too much stress must not be laid upon these slight changes in the wire. The difference between Series 9 and Series 8 is small and may have its origin in a slight change in the working condition of the apparatus caused by its period of idleness. The important fact is that no great change occurred and the wire was in practically the same condition as when left. The explanation of the difference in slope in some of the curves is that the experimental error is of about the amount of the variation. The total change in Young's modulus over the entire temperature range is only 10 per cent. and the difference in stretch which this represents corresponds to less than one revolution of the micrometer head. In order to show this variation the scale to which Young's modulus is plotted has to be so large that the errors of observation become appreciable. When the magnitude of the probable error is taken into consideration the consistency of the curves taken under such a variety of conditions is remarkable.

CONCLUSIONS.

The following conclusions apply to the sample of copper wire that has been studied. I am of the opinion that other specimens of copper will yield results differing only in the magnitude of the changes, and believe that the results are very suggestive of the effects that can be expected in other metals. But work with iron wire now under way and certain results of other investigations to which reference is made later makes me feel that too great caution cannot be exercised in making general conclusions from observations upon particular samples.

From the preliminary observations and the tests upon specimens Nos. 2 and 3 we reach these conclusions:

1. A copper wire can be brought to a steady elastic state in which the stretch modulus becomes a function of temperature. In the present instance it was brought about by repeated stretching and heating and cooling over a range of temperature of 20° C. to 150° C. The preliminary tests show that the rate at which the heat was applied or at which the wire was cooled, the length of time the temperature was maintained, and the thermal route by which a given temperature was reached had no apparent effect upon the value of the modulus at any given temperature. These same facts are brought out still more convincingly by the extended work upon specimens 2 and 3, which also show that permanent changes in the modulus can be practically eliminated by a relatively small amount of heating and stretching, which if continued for a longer time renders them negligible.

2. Heating by an electric current has no effect other than that caused by the accompanying temperature. This was proved for one temperature by the results of Table I. and at a number of different temperatures by the work of Series 7, Wire 2, shown in Fig. 6, in which the heating was alternately by current and the external source.

Further proof with step by step heating is also furnished by the identical nature of the results recorded in the four curves of Fig. 4, two curves of which are for current and two for external heating. Conclusive evidence is afforded by the long series of experiments carried out upon the third specimen, in which every possible way of varying the methods of heating was attempted without detecting any difference in the results.

3. Young's modulus of a copper wire decreases with increase of temperature at an increasing rate. In the case of the specimen studied, the amount of decrease at different temperatures in terms of per cent. of the value of the modulus at 20° C. is as follows: 40° C., 0.6 per cent.; 60° C., 1.7 per cent.; 80° C., 2.9 per cent.; 100° C., 4.6 per cent.; 120° C., 7.0 per cent.; 140° C., 10.0 per cent. At 20° C. the modulus of the sample in the steady elastic state was 11.5×10^{11} dynes per cm^2 .

The true nature of the temperature change was first shown by the work with specimen 2 as represented by the curves of Figs. 4 and was fully substantiated by the further work with specimen 3 which yielded identical results.

4. Heating and repeated stretching increases Young's modulus. As is shown by the results with specimen 3 there is an apparent increase of about 5 per cent. caused by the first four heatings and the accompanying stretching, which is thought to be due in part to the straightening out of the kinks. But there was a further increase of 2 per cent., which was a true history effect, although caused probably as much by the repeated stretching as by the heating.

COMPARISON WITH RESULTS OF OTHERS.

As has already been stated previous results upon the effect of current do not agree. A comparison of these with the present work will not be attempted as the degree of accuracy in the latter is far greater. The conclusion that there is no effect of current upon copper other than that caused by temperature can be accepted to an accuracy of less than 1 per cent.

An interesting comparison regarding the history effect and the magnitude of change with temperature is furnished by the work of Shakespeare,¹

¹ Loc. cit.

who used interference methods to determine the modulus at 13° C. and at 100° C. He does not compute the value of the modulus but gives the change from 13° C. to 100° C. as 3.6 per cent. For this range the present specimen shows a change of 5 per cent. Shakespeare also found that the modulus increased with continued heating and cooling, until a permanent state was reached. The first heating produced a sudden increase of several per cent. which was followed by a gradual change. Nine heatings produced a total increase of 12 per cent. The permanent change described in this paper was of the same kind and amounts to 7 per cent.

In the following comparison of results upon the temperature effect the bracketed figures are taken from our own curves. At 20° C. our value of Young's modulus was 11.5×10^{11} dynes per cm^2 . Miss Noyes¹ found the modulus of a specimen of copper to be 12.02 at 20° C. This and another specimen tested at temperatures up to 150° C. gave a uniform decrease of the modulus which computed for 20° C. to 140° C. gives a change of 8.5 per cent. and 16 per cent. respectively [10 per cent.]. At 17.4° C. Gray, Blyth, and Dunlop² found the modulus of a sample of commercial copper to be 11.15 and of hard drawn electrolytic copper at 19.5° C. to be 12.9. They made tests over a range of 100° C. and reported a uniform rate of decrease which computed for 20° C. to 100° C. gives for the two samples changes of 1.2 per cent. and 3.4 per cent. respectively [4.6 per cent.].

Slotte³ found for two specimens changes of 6.6 per cent. and 4.2 per cent. respectively [1.5 per cent.], for a temperature increase from 20° C. to 60° C. The moduli at 20° C. were respectively 12.4 and 12.7. The more important point is that he did not find a uniform rate of change. The modulus of the former specimen decreased at an increasing rate while the latter shows a decrease at a decreasing rate. Decrease of the modulus at an increasing rate is also indicated by the work of Wertheim.⁴ If his results at 15° C., 100° C., and at 200° C. are plotted and a smooth curve drawn it is almost identical with our own curves, except that the values are about 10 per cent. lower. Regarding the nature of the change observations on the torsion modulus are valuable although too great stress must not be placed on them. Kohlrausch and Loomis⁵ made observations upon copper at various temperatures. They found an increasing rate of change as the temperature increased. Computed for 20° C. to 100° C. the change is 4.2 per cent. [4.7 per cent.], and for 20° C. to 140° C. 7.5 per cent. [10 per cent.]. Slotte⁶ has also made a study

¹ Loc. cit.

² Loc. cit.

³ Loc. cit.

⁴ Loc. cit.

⁵ Loc. cit.

⁶ Loc. cit.

of the torsion modulus of copper and finds the same increasing rate of change. Corresponding values from his work are 5.9 per cent. and 8.3 per cent.

The results that have been cited must be considered from two stand-points, first as to the general nature of the changes of Young's modulus, whether uniform or otherwise; and secondly, regarding the numerical values.

Examination of the methods of those who have reported a uniform decrease shows that their work was not of sufficient accuracy to have detected the variation from a linear relation found by others. We are not certain how much importance should be attached to the work of Slotte upon Young's modulus. He worked also with aluminum, iron, and platinum as well as copper and found a decreasing rate of change. None of these results seem to have been repeated. The torsion modulus can be determined to a much higher degree of accuracy and Slotte's recent work upon the torsion modulus of all these metals shows an increasing rate of change. Since the evidence that is available points toward a similarity in the nature of the temperature change of the two moduli this raises a question as to whether Slotte's former results upon Young's modulus are a true temperature effect.

With the results of Wertheim and of Slotte upon one specimen agreeing with our own and the work of Kohlrausch and Loomis and of Slotte upon the torsion modulus showing the same general type of change, I believe that the conclusion that Young's modulus of copper decreases with increase of temperature at an increasing rate has sufficient corroboration.

A comparison of the numerical values of Young's modulus and of the temperature coefficient, ample allowance being made for experimental error, leaves no doubt as to the importance of chemical purity, method of preparation, and size of specimen. It is possible that samples of copper may be found that will show effects peculiar to current heating, or will not give modulus-temperature curves of the simple form that I have found, but I am inclined to believe the main differences will be found in the magnitude of the coefficients. Undoubtedly further work will reveal some relation between the chemical composition, the coefficient of linear expansion, the electrical conductivity, and other physical constants, and the value of Young's modulus and its rate of change with temperature. Investigation is under way upon other metals in order to study the effect of current, to determine the temperature coefficient of Young's modulus, and to study the relation between the temperature changes of the two elastic moduli.

In conclusion I wish to acknowledge indebtedness to the staff of the physical laboratory of the State University of Iowa for their interest in the work and especially to Professor G. W. Stewart for suggesting the problem and to Professor J. N. Pearce, of the department of chemistry, for the chemical analysis.

PHYSICAL LABORATORY
STATE UNIVERSITY OF IOWA,
August, 1913.



THE SENSIBILITY CURVES FOR SELENIUM; A NEW SENSIBILITY-WAVE-LENGTH MAXIMUM AND A NEW PRINCIPLE.

By F. C. BROWN AND L. P. SIEG.

RECENTLY Pfund¹ found a maximum in selenium at wave-length $690 \mu\mu$ which disappeared when the intensity of illumination became very faint. This disappearance calls attention to the complexity of the light action in selenium. The present authors were led to believe as a result of a mathematical analysis that the complex behavior might be simplified by using very short periods of exposure to the light, and even that the maxima might disappear for intense illumination also. We have been surprised to find in the Giltay cell a very pronounced maximum at $800 \mu\mu$, which disappears with small intensity just as the maximum discovered by Pfund in the region of $690 \mu\mu$ was observed to vanish. And further, not only does this maximum disappear with intense illumination when the selenium is exposed for a short interval of time, but all maxima disappear, such that the remarkable result is obtained that the change of resistance of the particular cell studied is independent of the wave-length of the incident light between 460 and $790 \mu\mu$. The change of resistance for light in this region is solely a function of the intensity. This last conclusion is important in that it promises us an instrument for measuring energy in the visible spectrum more delicate than the thermopile or bolometer. In this article we propose to restate the conditions under which the maxima appear and to define a method of using the selenium cell for energy comparisons of the various wave-lengths in the visible spectrum.

THEORY.

First we wish to make clear that for intense illumination made up of all visible wave-lengths, we should obtain the simplest conditions by using short exposures. A mathematical analysis has revealed² that for the Giltay cell when exposed to approximately white light there are two direct and two reverse changes taking place and only one conducting

¹ PHYS. REV., XXXIV., p. 370, 1912.

² See paper by F. C. Brown, PHYS. REV., 33, p. 403, 1911.

element. On p. 408 of the article referred to are given the rates of change and the constituents of the cell under specified conditions. For a short exposure at 18° C. the changes in the conductivity are made up relatively as follows:

$$\begin{aligned}
 A \rightarrow B = \alpha_1 A &= 11,200 \times .054 = 604 \\
 A \leftarrow B = \alpha_2 B &= .8 \times 12 = 9.6 \\
 B \rightarrow C = \beta_1 B &= .8 \times .9 = 0.7 \\
 B \leftarrow C = \beta_2 C &= 3.6 \times .004 = 0.0
 \end{aligned}$$

Thus it appears that we obtain appreciable changes only between the A and B components, and of these the direct change constitutes about 98 per cent. of the total. But for long periods of exposure the amount of each of the four changes above noted approaches equality, as A becomes less, and B and C become greater. The analysis shows therefore that the short exposure gives simple and single changes, while any long exposure gives a most complex and varying summation, because the amounts of A , B and C are continually changing with time. Maxima obtained for long exposure really have very little meaning until we first establish what part of the maximum can be sorted out and attributed to the direct change from A to B .

But aside from what has just been said, short exposures should give a constant change, because for a short interval the amounts of the A , B , and C components are approximately fixed, and since the rates of change are unvarying under given conditions, the sum of $\alpha_1 A - \alpha_2 B - \beta_1 B + \beta_2 C$ should be constant. For any long interval the interchange of the components makes the process very complex.

We therefore decided to map out the sensibility of the selenium for equal energy throughout the spectrum, by exposing the selenium for only a fraction of a second, using sensibility curves for longer exposure merely for comparison.

There is nothing so far in the theory to indicate why short exposures should or should not give sharp maxima. Short exposures however should give simple conditions.

ARRANGEMENT OF APPARATUS AND METHOD OF MEASUREMENT.

To obtain the sensibility curves, the principle laid down by Pfund¹ was followed. The change of resistance for equal energy was measured throughout the visible spectrum. The arrangement of apparatus is shown in Fig. 1. Light from a Nernst filament, N , manufactured by Pye and Co. for their lamp and scale outfit, is focused by the lens L , on the collimating slit S_1 of a constant deviation monochromatic illuminator,

¹ Phil. Mag., Jan., 1904.

manufactured by Spindler and Hoyer. The Nernst glower was maintained at constant intensity by using storage battery for heating current. The bundle of quasi-homogeneous rays was then focused on the slit S_2 , and from there was focused by means of the concave mirror M , upon either the thermopile slit or the selenium cell, as desired. The lenses of the monochromatic illuminator were 20 mm., or $f/12.7$ in diameter, and hence with this apparatus, much of the energy is lost. A new illuminator of greater light-gathering power has been obtained and will be used for future work. The slits S_1 and S_2 were kept of equal width, which varied from 0.2 to 1 mm. The length of the slits was one centimeter.

The thermopile was of the Rubens type, but it was of bismuth-silver wires of the improved design of Dr. W. W. Coblenz. It was remarkably

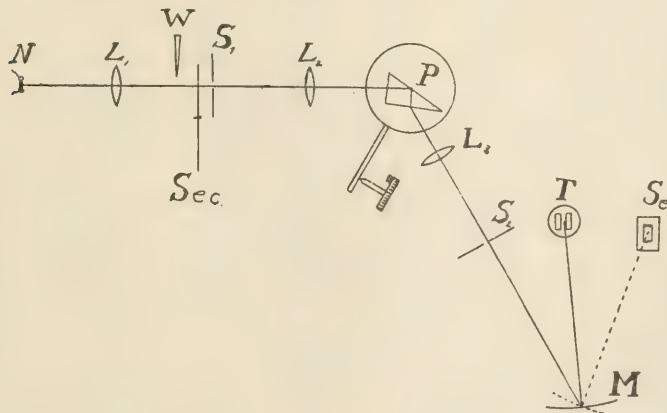


Fig. 1.

free from drift and altogether very satisfactory, as used with a Thomson galvanometer made by Siemens & Halske. The galvanometer had a resistance of 5.4 ohms, and the thermopile had a resistance of 7.4 ohms. This combination when a glass cover was in front of the thermopile junctions gave a deflection of 300 divisions with a candle at a meter. The period was about 5 seconds for this sensibility. By increasing the period the sensibility could have been increased several times, easily to more than 1,000 divisions per candle per meter.¹

¹ Since the above test was made we have received a standard carbon incandescent lamp from the Bureau of Standards, calibrated for total radiation in a given direction. By means of this standard lamp we found the sensibility of the thermopile to be 9.3×10^{-8} watts/mm. deflection on our scale. It must be remembered that this sensibility was obtained with a glass cover over the thermopile. Had this cover been removed, the sensibility would have been much greater.

A Giltay cell, the one previously studied by one of the authors, was used.¹ It had a resistance of 299,000 ohms in the dark with 4 volts in the circuit, or 270,000 ohms with 20 volts. It was connected in a Wheatstone bridge. For the long exposures a potential of 4 volts was left in the circuit continuously, but for the exposures of a fraction of a second duration the potential was changed to 20 volts. During the experiments the temperature did not vary from 24° by as much as one degree. For the long exposures a Leeds & Northrup high sensibility galvanometer of about 1,000 ohms was used. For the short exposures the method outlined by Brown and Clark² was adopted. With this a ballistic galvanometer of 22 seconds period was substituted for the above galvanometer.

We deviated from the procedure outlined by Dr. Pfund in two essentials. An exposure of a fraction of a second was used, and secondly we did not give the cell a special treatment of the nature of preliminary exposure before making each observation. Aside from the advantage of simplifying the conditions, the short exposure has the advantage in that a shorter time is necessary for recovery. We do not believe in the special treatment immediately before making an observation, because such only exaggerates the complexity, and makes it more difficult to define the characteristics of a given sample of selenium. Each distinct preliminary treatment should give a corresponding distinct sensibility curve, providing only that the special treatment varies either in duration or nature of action on the slow rates of change in the selenium.

The intensity of illumination was varied by a rotating sector disc, *Sec*, and an optical wedge, *W*, (Fig. 1) either singly or in combination. It was very easy by this combination to verify the applicability of Talbot's law. However we did not make as extensive a verification as was made by Pfund.

The total area of the selenium exposed was about 4 mm², which was only a little more than a thousandth part of the entire sensitive surface. The fact that only such a small portion of the selenium was exposed was marked only by an apparent decrease of the sensibility of the selenium by a constant value.

We first obtained a family of sensibility curves with varying energy intensity on the selenium using long periods of exposure, 30 sec. In general the energy on the thermopile was adjusted to constant deflection of the galvanometer (20 div.) or to within five per cent. of this value. Then the selenium was exposed to this same bundle of energy. The slit width was 0.2 mm. This width gave a very sharp maximum (see

¹ PHYS. REV., 33, p. 403.

² PHYS. REV., 33, p. 53, 1911.

Fig. 2) at 800 $\mu\mu$, a maximum less sharp and much less pronounced at 690 $\mu\mu$, and a broad maximum extending from 540 $\mu\mu$ to 600 $\mu\mu$ (Fig. 2). In obtaining Curve C a different practice was resorted to. First the energy from a Nernst glower was measured throughout the spectrum. And then to obtain equal energy on the selenium the calibrated sector disc openings were adjusted in inverse ratio to the energy in the different parts of the spectrum. This method had the advantage of picking out the characteristics of the curve quickly and with a small number of observations, but it required supplementary readings by the other method in some instances in order to obtain higher precision in the relative values of adjacent points. The energy intensity which gave curve A was

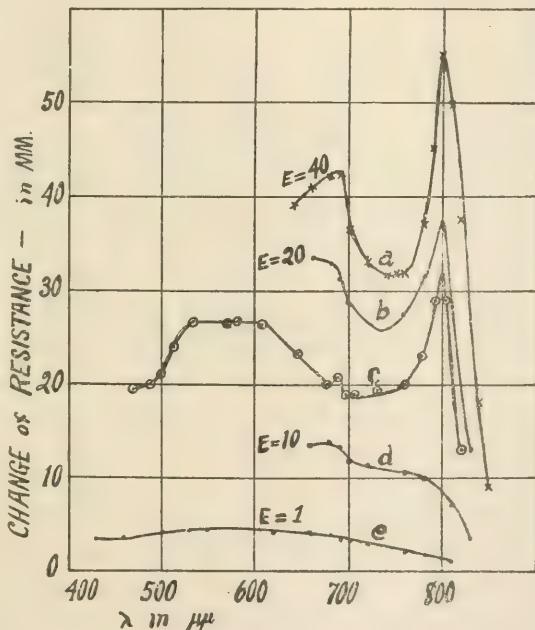


Fig. 2.

about that of a candle at four meters. The intensity of exposure on the selenium was decreased by use of the sector disc by steps, until it was diminished to one fortieth of the above value. The curves are shown in Fig. 2.

The points of interest are first that there is a sharp maximum at 800 $\mu\mu$ which has not hitherto been observed in selenium, and second that faint energy will not bring out this maximum. This last point is very similar to Pfund's observation. The vanishing of the maxima with faint illumination may be explained in terms of the rates of change

existent in selenium. For faint illumination all the rates of change are small, particularly are α_1 and α_2 small in comparison with their values for intense illumination. This simply means that in a 30-second interval with faint illumination there is only time for the *A* component to be transformed into the *B* component and of the original *B* component to be transformed into the *C* component, and that of the *B* component for example the excess formed by the light is so small in this time that only the original amount need be considered in the formation of the *C* component. A long exposure to faint illumination tends to approach the same simplicity that a short exposure to intense illumination accomplishes.

We next tested the effect of varying the time of exposure to intense light referred to in the theory to see if the maximum would tend to vanish. The new duration of exposure was .4 sec. and the slit width was one millimeter. The energy beam was focused on the selenium, so that we obtained a somewhat greater energy intensity than any which gave the curves in Fig. 2. The observations were found to agree with each other very well indeed; five observations were taken for each setting of the illuminator except one. One division on the scale was usually the maximum variation obtained. For the selenium the error was not as great as one per cent. However it was not easy to assure the individual thermopile readings to a greater accuracy than five per cent.

The Curve *A* (Fig. 3) shows the average of the deflections of the ballistic galvanometer, *i. e.*, the change of resistance, between 500 $\mu\mu$ and 810 $\mu\mu$. It is altogether probable that the single point that is off the curve was off as a result of error due to insufficient number of thermopile readings. By the method that we used it was necessary to diminish the energy in order to make observations beyond 500 $\mu\mu$. By diminishing the energy to 1/20 of the original value the Curve *A*₂ was obtained. The average of a large number of observations indicated that the independent relationship between wave-length and deflection extended back as far as 460 $\mu\mu$.

The Curves *B* and *C* represent the observations for long periods of exposure to the same intensity as above mentioned. The ordinates for Curves *B* and *C* are arbitrary and do not correspond to those for Curve *A*. It is observed that a 60-second exposure (Curve *C*) makes the maxima and minima slightly more pronounced than a 30-second exposure (Curve *B*). Perhaps a difference curve between an exposure curve for a very long time and one for a very short time would give a sensibility curve arising solely from the slow changes in the selenium. However this has not been carefully thought out yet. Observations taken after quickly repeated exposures, particularly to longer wave-lengths, tend to smooth

out the maxima. Dr. Pfund has had the kindness to communicate some very interesting and as yet unpublished results by Mr. P. J. Nicholson which are directly in agreement with our result, viz., that the slow rates of change arise from light of the longer wave-lengths. His results show that the form of sensibility curves is markedly altered by varying the wave-length of the preliminary exposure, and that under the continued influence of infra-red radiations ($800 \mu\mu$), the usual fatigue

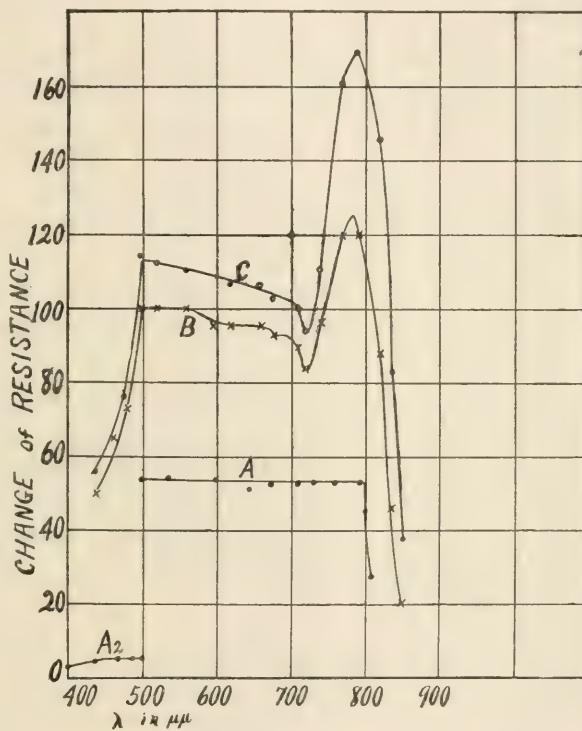


Fig. 3.

A is for 0.4 second exposure; *B* is for 30 seconds exposure; *C* is for 60 seconds exposure.

and lag almost disappear. The fatigue and lag seem to us merely evidences of the slow changes in conductivity.

Having received a more powerful illuminator we are extending our work, to find out the limits in which the change of resistance is independent of the wave-length for short exposure, to establish the law of change of resistance with intensity, and to compare other varieties of selenium and light-sensitive materials.

It is interesting to note how rapidly the curve falls off beyond $800 \mu\mu$. We are unable to account for a mechanism that would produce a sudden jump of this kind.

The minima as well as the maxima arise from the longer periods of exposure. It may be that minima indicate the normal states for short exposure for particular wave-lengths, which means that spurious maxima arise from slow changes.

SUMMARY.

1. The sensibility curve for a Giltay cell has been determined under varying conditions.
2. In accordance with theory it has been shown that long periods of exposure give varying degrees of complexity, and are responsible for the regions of maximum sensibility.
3. By long periods of exposure a new maximum is obtained at $800 \mu\mu$.
4. By exposures of a fraction of a second the maxima and minima vanish and between about $460 \mu\mu$ and $790 \mu\mu$ the change of resistance is independent of the wave-length.
5. The work thus far accomplished emphasizes the importance of defining simple conditions for obtaining the maxima of such a complex acting agent as selenium.
6. The maxima and also the minima in the Giltay cell studied arise from the slow rates of change.
7. A selenium cell of this type by virtue of the independence of wave-length for short periods of exposure promises to be the most delicate instrument constructed for measuring energy within the range noted.

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CERTAIN EXPERIMENTS IN SOUND DIFFRACTION.

BY G. W. STEWART AND HAROLD STILES.

THE general character of sound diffraction is well understood and there is little likelihood that experimental study in this field will lead to important discoveries. Nevertheless such experimental examination is highly desirable. The selection of experiments recorded in this paper was influenced by apparatus already constructed and immediately available.

THE SHADOW OF A RIGID SPHERE.

The theoretical investigation of the acoustic shadow of a rigid sphere was first made by Rayleigh¹ and was later extended by one of the writers² to the more general case where the distance from the sphere concerned is not limited. This theory was tested by the writers³ and it was found that the experimental results varied from theoretical prediction in a manner indicating errors due to the distortional effect of resonance.

Apparatus.—In those experiments the source of sound was located on a hollow cement sphere, circumference 135.9 cm. This sphere was mounted near the edge of the roof of the physics building and the sound issued from it in a 5 cm. pipe opening. The sound-measuring device was a modified form of Rayleigh disc described in a previous article.⁴ The sphere was rotated about a vertical axis which permitted the disc to remain stationary. The sound was produced by an electromagnetically operated tuning fork, 256 d. v., mounted on a resonator box which was introduced into a funnel from which the sound was conducted 7 meters to the vertical pipe entering the sphere.

The same sphere was used in the experiments here recorded but the disc was removed to the floor below and a 5 cm. pipe led from the disc to the position desired in the neighborhood of the sphere. The constancy of the source of sound was all that could be desired. The contact terminal attached to the fork was a short helical spring, 0.3 cm. in radius, of platinum wire, No. 29 B. and S. gauge. When the fork was actuated by storage battery voltage, it would operate for an hour without a change in its amplitude of one per cent.

¹ Rayleigh's Theory of Sound, 1896, Vol. II., p. 254.

² Stewart, PHYS. REV., Vol. XXXIII., No. 6, Dec., 1911, p. 467.

³ Stewart and Stiles, PHYS. REV., Vol. I., No. 4, April, 1913, p. 309.

⁴ See Stewart and Stiles, loc. cit.

As shown in Fig. 1, the sphere was rotated about a vertical axis. The Rayleigh disc was removed to the inside room below to prevent the disturbance due to air currents and to decrease the absorption due to resonance at the sphere, it having been observed that both of these errors were serious. With the pipe placed as shown in Fig. 1 the intensity produced in it was strictly proportional to the potential energies at the opening. The disc in the room below was attached directly to the pipe. Fortunately, the pipe length was such that there was no tendency for resonance. This statement is verified by the results.

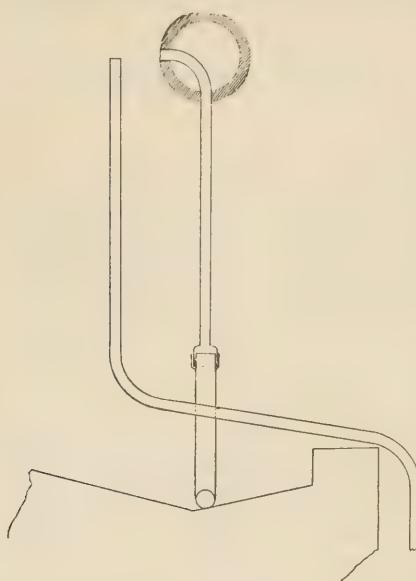


Fig. 1.

The improved apparatus demanded a more sensitive disc and this was obtained by inserting a finer quartz fiber. The period of the disc became 15 seconds.

The theory.—The mean potential energy per unit volume is given by the expression,¹

$$\frac{1}{2}\rho_0(F^2 + G^2)(k/2\pi r \iint U dS)^2.$$

The relative intensities are therefore given by relative values of $F^2 + G^2$. The pipe opening remained at a constant distance r from the sphere center and various values of intensities were obtained by rotating the sphere, this being equivalent to a stationary sphere with the intensities measured at various points in a circumference whose plane includes the diameter of the sphere passing through the source of sound. The relative values of intensities computed as indicated in a previous article² for $kr = 2$, are for 0° (the position shown in Fig. 1), 1.00; 30° , 0.560; 60° , 0.187; 90° , 0.065; 120° , 0.034; 150° , 0.033; 180° , 0.033.

Results.—The results obtained for a distance from the center of the sphere equal to twice its radius are shown in Table I. This gives a record of four series of observations. The deviations from the mean can be accounted for by the smallness of the deflection, about 2 cm., and the error due to the setting of the sphere at 30° where the intensity changes

¹ For derivation and meaning of symbols see Stewart, loc. cit.

² For numerical values see Stewart and Stiles, loc. cit.

rapidly. In order to compare these results with the theoretical values and to show the great improvement over the earlier experimental arrangement, both the present and former results are plotted in Fig. 2, and the theoretical values are shown by the full line curve. The earlier results are represented by crosses and the later ones by small circles. The

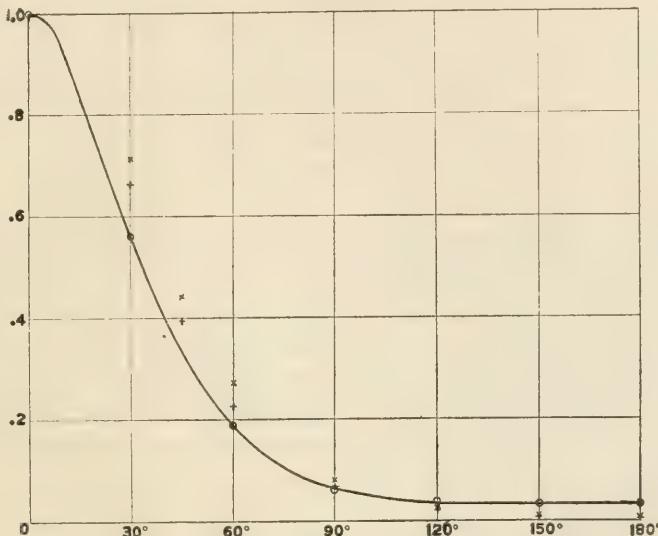


Fig. 2.

TABLE I.

	0°	30°	60°	90°	120°	150°	180°
	1.00	0.580	0.230	0.067	0.035	0.025	0.025
	1.00	0.625	0.175	0.050	0.035	0.035	0.035
	1.00	0.555	0.170	0.050	0.040	0.035	0.030
	1.00	0.475	0.185	0.075	0.045	0.040	0.035
Mean	1.00	0.558	0.190	0.060	0.039	0.034	0.031

agreement between theory and experiment is better than could be expected. Our belief is that the errors in the earlier results were due to air currents and to the absorption caused by resonance. The distortion produced by the latter would have the effect of "ironing out" the curve, and the former observations show that that is the case.

The verification of the theory is very satisfactory. This increases our confidence not only in the theory, but also in the Rayleigh disc. So far as we are aware, there has been no study which has shown that the deflections of the disc are proportional to the potential energy at the opening of the disc tube. It is true that the correctness of the theory

of the disc has been experimentally¹ verified so far as the relation between the kinetic energy of the air at the disc and the deflection of the disc are concerned. The writers attempted to show the proportionality of the disc deflection and the potential energy at the disc tube opening by observations of the amplitude of the fork and the deflection of the disc when both were placed in the same room. The dimensions of the room were about 25, 7, and 4 meters. The temperature as measured by wall thermometers was constant to within 1° C. It was found that, if comparisons were made quickly over the range of deflection of the disc, there was a constant proportionality between the square of the fork's amplitude and the deflection of the disc. But the apparent sensibility of the disc measured in this manner changed with time. In other words, the ratio of deflection to the square of the amplitude changed from moment to moment, being quite appreciable in a few minutes. The explanation seemed to be that the maxima and minima intensities shifted their locations with changes in temperature. The changes, however, seemed greater than could be produced by standing waves caused by only one reflection. This might have been anticipated. These tests satisfied our minds of the correctness of the assumption of proportionality of deflection and intensity at the tube opening.

PASSAGE OF SOUND THROUGH NARROW SLITS.

Rayleigh has investigated the passage of sound through narrow slits both theoretically² and experimentally.³ The result of the former can be briefly presented. Consider an aperture in a thin plane screen of infinite extent. Let a plane wave be incident from the left. Its velocity potential, omitting the harmonic time factor and considering the modulus unity, is $\varphi = e^{-ikx}$. Consider the conditions without aperture and then the supplementary values of the velocity potential representing the changes produced by the aperture. By addition, the velocity potential on each side of the screen is obtained. The resulting velocity potential at a great distance, r , on the right side is,

$$\varphi = e^{-ikr} \frac{M}{r}$$

or

$$\varphi = \frac{M}{r} \cos^{\kappa(nl-r)},$$

where k is $2\pi \div$ wave-length and where M is the "capacity." The term

¹ Zernov, Annal. d. Phys., No. 26, p. 79, 1908.

² Rayleigh, Phil. Mag., XLIII., p. 259 (1897); Scien. Paper IV., p. 291.

³ Rayleigh, Phil. Mag., XIV., p. 153 (1907).

"capacity" is used because M is the total quantity of electricity which can be distributed over the aperture in a manner to produce a uniform potential of unity over the aperture. It is known that for an ellipse,

$$M = \frac{a}{F(e)},$$

where a is the major axis, and small e the eccentricity, and F is the symbol of the complete elliptic function of the first kind. If the ellipse be very elongated,

$$M = \frac{a}{\log_e \left(\frac{4a}{b} \right)}.$$

Inasmuch as the only variable in the expression for the velocity potential at a fixed great distance, r , is M , the same values of M would determine the same sound intensities. The above formula shows that the intensity is much more sensitive to alterations in a than in b , the minor axis, and Rayleigh attempted to verify this by experiment. The difficulties he encountered were great, and in addition he depended upon ear memory for the reproduction of identical intensities. The arrangement of our Rayleigh disc and the possibility of experimentation practically free from reflection, tempted us to test the above formula.

For the infinite plane a rectangular piece of galvanized iron 33×38 cm. was utilized, the dimensions and shape being accidental. This plate was fastened on the horizontal end of an elbow placed upon the end of the pipe shown in Fig. 1. In the center of the vertical plate an opening 0.8×4.0 cm. was made, and over the opening was constructed the slit. Four small safety razor blades, 1.8×4 cm., beveled on both sides, were used. Three were placed in the same plane and to the fourth was attached an edge made out of a copper strip, whose thickness was the desired width of the slit. Changes in the slit width required different copper strips. Changes in the length could be readily obtained by sliding the fourth blade with its attached copper strip. Vaseline was freely used to stop all openings and was found entirely satisfactory.

The source of sound was the electrically operated tuning fork with the open end of the resonator mounted directly in front of the slit and about 150 cm. distant.

Our first experiments were made with sharpened brass edges but these were found unsatisfactory when the slit became narrow. Experiments with these edges with a width of 1 mm. ($b = 0.5$ mm.), showed that the variation of intensity with length was practically linear. This fact simplified our experiments with the razor blades. We obtained a deflec-

tion with a 17.5 mm. and b 0.1 mm., then a deflection with a 17.5 mm. and b 0.5 mm. and finally a deflection with a 10.0 mm., and b 0.5 mm. The ratio of intensities of the first and second slits were found to be approximately 0.52, the separate values being 0.51, 0.49, 0.55. The ratio of intensities of the third and second was approximately 0.49, the separate values being 0.47, 0.50, and 0.49. By assuming that the linear relation above cited holds, it is readily seen that the value of a giving the ratio of 0.52 with b 0.5 mm., would be 10.5 mm. We would then have the same value of M for the two slits, 35. \times 0.2 mm. and 22. \times 1.0 mm. Substituting these experimental values, we have

$$M = \frac{a}{\log_e \left(\frac{4a}{b} \right)} = \frac{17.5}{\log_e \left(4 \frac{17.5}{0.1} \right)} = 2.66$$

$$= \frac{10.5}{\log_e \left(4 \frac{10.5}{0.5} \right)} = 2.37.$$

Thus the formula for M is verified as nearly as could be expected with the lack of conformity with theoretical conditions. For it is to be noted that the presence of the pipe behind the slit destroyed the plane of infinite area, and further, that there is resonance in the pipe leading to the disc. This resonance would of course be modified by the size of the aperture. Other experiments cited below would indicate that the error due to resonance is of the same order as the variation between the two values of the M given above.

PASSAGE THROUGH CIRCULAR APERTURES.

Tests were made by varying the area and by varying the number of circular apertures of equal area. The value of M for a circle is $2a \div \pi$ where a is the radius. If the velocity potential at a great distance is proportional to M , then the intensity at a given distance, proportional to $\dot{\varphi}^2$, is proportional to M^2 , or to a^2 . An experimental test of this relation did not prove satisfactory, for as M changed the resonance in the pipe was altered and the conditions of the experiment were thus seriously modified. The values actually obtained are shown in the accompanying table, Table II. The deflections were reduced to the same scale, the aperture F giving a deflection of unity. The ratio in the last column is the relation of experimental and theoretical values of M . The ratio varies not more than 10 per cent. from the mean for a range of radii from 0.42 cm. to 1.28 cm. These variations, as well as those for the

smaller apertures are accounted for by variations in resonance. The indications are, however, that if resonance could be avoided a close agreement between experiment and theory would be found.

The value of M for N circles is $N \times M$, and the corresponding intensity is proportional to $N^2 M^2$. If the M 's are not alike, the intensity is proportional to the square of their sum. A test was made as follows. Four circular apertures, each 0.30 cm. in radius were made in a screen, see Fig. 3, and intensities obtained by opening them separately and simultaneously as indicated in the accompanying Table III. The agreement between theory and experiment is indicated by the ratio in the last column. It should be observed that the variation is not great and can readily be

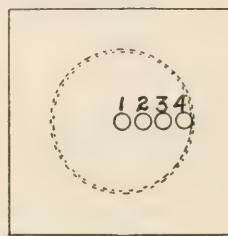


Fig. 3.

TABLE II.

Screen.	Deflection.	$\sqrt{\text{Defl.}} \times M$.	$2 a.$	Ratio.
<i>L</i>	5.45	2.34	2.56	0.91
<i>K</i>	3.67	1.91	1.88	1.02
<i>J</i>	2.00	1.41	1.27	1.11
<i>F</i>	1.00	1.00	1.00	1.00
<i>D</i>	0.56	0.75	0.83	0.90
<i>C</i>	0.20	0.45	0.60	0.75
<i>B</i>	0.06	0.25	0.40	0.62

TABLE III.

Apertures Used.	Relative Observed Values of Intensity.	Relative Values of M $\sqrt{\text{Intensity}} \times M$.	Relative Computed Values of M $M = M_1 + M_2 + M_3 + M_4$.	Ratio.
1	1.00	1.00		
2	1.00	1.00		
3	0.80	0.90		
4	0.58	0.76		
1 + 2	3.73	1.93	2.00	0.96
1 + 2 + 3	6.23	2.50	2.90	0.86
1 + 2 + 3 + 4	9.66	3.10	3.66	0.83

interpreted as due to change of resonance in the pipe. The variations of M for the separate apertures is doubtless due to the proximity of the apertures to the pipe. The arrangement is faulty also in that the apertures are close together. The lack of agreement between the experimental and theoretical results is explained by the lack of conformity

to theoretical conditions and the variation in resonance in the pipe. The latter seems to produce the greater error. Indeed, all the experiments with apertures indicate that the errors due to changes in resonance are of the same order as the differences between experimental and theoretical results.

The results with both slits and apertures show the difficulty of securing satisfactory experimental conditions. Experiments of this character should be continued with improvements in apparatus that will avoid the errors due to resonance.

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TELESCOPIC VISION OF AN ILLUMINATED SURFACE

By FRED W. VORHIES

INTRODUCTION

An interesting aspect of the subject of telescopic vision has been discussed in a series of articles written by Stoney.¹ In these articles Stoney discusses the subject from a theoretical standpoint but makes some suggestions as to how apparatus could be set up and used in verifying his theories and assumptions. It is the purpose of this paper to show how this apparatus works in practice and to give the results obtained by its use. In view of the fact that there has been so much discussion during the past, concerning the ability to see details upon such astronomical objects as Mars, the author trusts that this contribution will be of value. Reference should be made to Stoney's articles for the theory of his experiments, for it is too long to reproduce in full here.

As a basis for his theories Stoney makes the following assumptions which I adopted and proved to be correct:

(1) In studying an illuminated surface or object—the planet Mars, for example—the real object, No. 1, can be removed and a substitute, No. 2, can be used in its stead. No. 2 is to be a transparent object with the details of No. 1 delineated upon it.

(2) When No. 2 is illuminated from behind with diffused light, the same sort of image will be formed in the telescope as when No. 1 is illuminated from in front with diffused light.

(3) A lens can be placed immediately in front of No. 2 and the image which it casts of a point-source of light, placed at some distance (the light from this source passing through object No. 2), is called the concentration image.

(4) The introduction of this lens does not alter the optical conditions.

(5) One method of analysis permits us to consider that the ordinary telescopic images of illuminated surfaces are made up of an infinite number of the above concentration or partial images.

¹ *Philosophical Magazine*, 16, 318, 796, 950, 1908.

The above assumptions enable us to reduce the highly complex problem of image-formation by diffused light to a simple diffraction problem. It should further enable us to place, at least, an inferior limit to the image-forming power of our telescopes.

EXPERIMENTAL METHODS AND THEORY

Fig. 1 is a diagram of the experimental apparatus in its final form. M is a monochromatic illuminator which gets its light from an arc lamp. Light from M is focused by the lens L_1 on the pin-hole S , which acts as the point-source mentioned above, that illuminates the object (called No. 2 above) O . Behind and touching O is the achromatic lens L_2 which focuses the light from S upon the aperture A which is made separate from the camera C . This focused image of the point-source with its accompanying diffraction pattern, caused by the object O , is the concentration image which has been mentioned above. The camera represents our telescope and the aperture A represents the rim of the object glass.

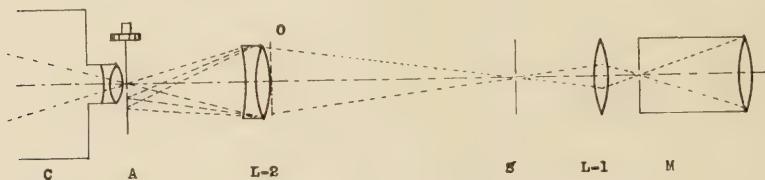


FIG. 1

The object O was made by drilling a hole 4.5 cm in diameter in a plate of copper. Across this, wire was placed, varying from 0.08 mm to 0.62 mm in diameter. This wire was placed in such a manner as to form details which could be studied in a photograph. The distance OA is determined by the focal length of the lens L_2 . In this case OA was 120 cm.

If we now suppose that the object O is to represent the planet Mars, we can obtain by means of Airy's formula,¹ which gives the diameter of the diffraction rings formed at A by a circular aperture of given size at O , when illuminated by a point-source at S , the size of the apertures that must be used at A to represent given

¹ *Wood's Physical Optics*, 2d ed., p. 237.

telescope objectives. Further, as I shall now show, the distance from O to A , the size of the object O , and the size of the aperture A can be so chosen as to give on the photographic plate an image of the same optical excellence as that obtained by a telescope of given size at a given distance from a heavenly body which is represented by the object O . In other words we can duplicate astronomical conditions in the laboratory.¹

In order to use Airy's formula, which refers to diffraction rings formed with a point-source of light, and apply it to an astronomical object seen by reflected diffused light, use must be made of the five assumptions made in the first part of this paper. Airy's formula for the fifth maximum diffraction ring is $\sin \theta = \frac{2 \cdot 361}{\gamma} \lambda$, where θ is the angle of diffraction, λ the wave-length of the light used, and r the radius of the lens casting an image of the point. In this work light of wave-length 0.000055 cm was used, and r , the radius of the planet Mars, was taken as 2,100 miles. Then $\sin \theta = \frac{2 \cdot 361 \times 0.000055}{2100}$. Again remembering, according to the assumptions, that the lens is immediately in front of the body (No. 2) substituted for the actual planet (No. 1), we get another expression for $\sin \theta$ which is given by the radius of the fifth diffraction ring divided by the distance, say 35,050,000 miles, from the earth to the planet Mars. From these two expressions the value of x is found to be 2.138 cm. $2x = 4.276$ cm, the diameter of the fifth maximum ring in the diffraction pattern from the object representing Mars.

According to Stoney's theory it is the relation of the aperture of the telescope to the diameter of the diffraction pattern that determines the excellence of the image. Perhaps it would seem from this that a telescope 4.28 cm in diameter should give an image of the planet. If we were dealing with ideal conditions, a telescope of this size might possibly give an outline of the planet, but the image would contain no details. It must be remembered that in nature we have an overlapping of a great many partial

¹ Optical conditions only have been duplicated. The assumption was made that the details on the planet Mars contrast against the surface as well as dark wires would against white paper.

images, and that the small telescope would not admit enough of these various patterns to form a satisfactory image.

We shall designate by the constant K the ratio of the diameter of the aperture of the telescope to the diameter of, say, the fifth bright ring in this diffraction pattern. If a 24-inch telescope is used, the value of K is found to be $\frac{24 \times 2.54}{4.276}$, or 14.27. This means that the diameter of the telescope is 14.27 times greater than the diameter of the fifth bright diffraction ring from Mars. This value of K we shall now use in determining the diameter of A , the aperture in the laboratory apparatus that is to replace the actual objective aperture of the telescope considered.

If the diameter of O is 4.5 cm and OA equals 120 cm, $\sin \theta = \frac{2.361 \times 0.000055}{2.25}$

$$\text{Also as above, } \sin \theta = \frac{x}{120}$$

$$\text{Eliminating } \sin \theta, x = .006928 \text{ cm,}$$

$2x = .013856$ cm, the diameter of the fifth bright diffraction ring from O .

$.013856 \times 14.27 = .1976$ cm, or about 2 mm, which is used as the diameter of the aperture which represents a 24-inch telescope in the experimental apparatus. Using this relationship, the sizes of the other apertures to be used are easily determined.

Table I shows the sizes of the apertures used and the diameters of the telescopes which these apertures represent in the experimental apparatus.

TABLE I

Aperture	Telescope
4 mm	48 inch
3	36
2	24
1.25	15
1	12
.6	7.2
.4	4.8

Returning now to the object of O , if 4.5 cm equals 4200 miles, the wires on the object which were 0.62 mm, 0.38 mm, and

0.08 mm, respectively, would equal 58 miles, 35.5 miles, and 7.5 miles respectively, on the planet Mars. These calculations were made because a great deal of discussion has taken place among astronomers concerning certain details upon the surface of the planet. So-called canals varying in width from 60 miles to 20 miles have been viewed by different astronomers. In order to investigate this point, I made the smallest details represent objects 7.5 miles in width. The pattern formed by these wires was chosen quite at random and in no way is supposed to represent the map of Mars. The things that are faithfully represented are the disk of Mars at this given distance, and dark objects of the sizes specified.

If an incandescent lamp behind a ground-glass screen were placed at *S*, instead of the point-source of light, there would be an infinite number of point-sources. Each of these sources or points would be capable of illuminating *O* and would thus give its diffraction pattern at *A*, or, as we have said, a concentration image. The advantage, then, in using the point-source *S* is simply to cut down the complexity of the diffraction pattern at *A* and in turn to simplify the image produced in the camera *C*. Then again, if this diffused white light were used, there would be a large number of different wave-lengths in operation. This is simplified by using the illuminator *M*. By the use of these two devices the image is greatly simplified and a study of it is much more easily made.

Upon examining the diffraction pattern at *A*, it is found that it consists not only of the usual bright central spot surrounded by bright and dark rings caused by the circular form of the object that represents Mars, but also in the field there are bright and dark patches which are spectra caused by the wires used to represent superficial details on the planet. Now any part of this pattern, when admitted into the camera or telescope, is capable of giving some kind of an image of the object *O*. This fact permits one more step in the analysis and gives a means of obtaining partial images on the sensitive plate. Under ordinary conditions most of the light is contained in the central bright spot and the first five or six bright rings. This being true, if this part of the pattern is admitted into the telescope, a good image should be obtained. If this part of the pattern does not enter the telescope, the image

will not be so good, the quality depending on the particular part of the pattern admitted. It is an interesting fact that if only the central maximum is admitted by the telescope aperture, we get no image of the object, although a large amount of light will be admitted. This is in conformity with Abbe's theory of image-formation.¹

The above discussion now permits the insertion of two important definitions. The image obtained on the sensitive plate when the diffraction pattern from a point-source is admitted into the telescope or camera is called a partial image. If the central bright spot falls symmetrically within the aperture of the camera objective, an optimum partial image is formed. This seems to be the best image that it is possible to obtain of a given object with a given aperture, and is theoretically better than any image of a similar object taken under similar conditions with diffused light. In other words, with this laboratory apparatus we not only can imitate astronomical conditions, but can obtain even better images than are possible under natural conditions, because we can control the number of partial images that go to make up the final image. If the aperture A is moved to one side, the central bright spot will not be admitted into the camera and the image obtained will be formed by light from some part of the outer diffraction pattern. This image is one of the inferior images which, along with all the other partial images, good and inferior, go to make up the natural image of the object. From this it is easily seen that telescope images of bodies illuminated by diffused light are simply the result of an infinite number of partial images, and that instead of having one diffraction pattern falling within the camera, there is an infinite number of these patterns. It is then quite obvious that a natural image cannot be as good as an optimum image, because the natural image can be considered to be made up of the optimum and a number of other images which are very inferior. As the experimental results show, a natural image may approach the optimum in excellence but it cannot equal or surpass it.

EXPERIMENTAL RESULTS

The experimental results of this work are found in the accompanying photographs. Plate X contains four series of partial images

¹ *Wood's Physical Optics*, 2d ed., p. 223.

taken with different sized apertures. Series 1 was taken with a 2-mm aperture and represents the partial images that go to make up the actual image that would be seen with a 24-inch telescope. No. 1 was taken with the central bright spot of the diffraction pattern focused in the center of the aperture. This is what we call an optimum image and is better than any that can be obtained in actual practice under the same conditions. Nos. 2-8 were taken by moving the aperture of the camera to one side by means of the micrometer screw. The aperture was moved one half-millimeter each time. This means that No. 8 was produced by that part of the diffraction pattern 3.5 mm out from the central bright spot. Now it can be seen that in actuality there would be an infinite number of these partial images, and that the images we obtain with optical instruments are produced by an infinite number of these partials, interfering as they are superposed by a lens or by the eye. The increasing inferiority of the partial images as we go from 1 to 8 is to be noted.

The phenomenon of the change in appearance of the lines from black to white can be accounted for by the laws of diffraction. It will be noticed in the last part of each series that the horizontal wires almost disappear. This is caused by the movement of the aperture *A* to one side. After it has been moved 2 or 3 mm, it is in such a position that the parts of the diffraction pattern that enter the camera are altogether those caused by the perpendicular wires. This part of the pattern is not capable, therefore, of giving images of the horizontal wires. Investigations on a similar problem have been made with ordinary wire screens.¹

No. 9 is what we might call the composite image. It is to be taken as an approximate imitation of a natural image. It is obtained by superposing the exposures 1-8 on the same plate, giving equal times of exposure to all eight. From the discussion above the conclusion would be drawn that this image, No. 9, should not be as good as No. 1. In series 1 a very little difference can be seen between 1 and 9. This is because the excellence and large number of the good images in the series outweigh the defects contributed by the poorer images. This point is made more clear by the following series. Series 2, 3, and 4 were taken exactly as

¹ A. B. Porter, *Philosophical Magazine*, 11, 154, 1906.

series 1, with exactly the same lateral movement of the aperture A , and show the effects of smaller apertures. Series 2 was taken with a 1.25-mm aperture representing a 15-inch telescope, series 3 with a 1-mm aperture representing a 12-inch telescope, and series 4 with a 0.6-mm aperture representing a 7.2-inch telescope.

It will be noted that as the aperture decreases in diameter, the number of good images decreases and that No. 9, the composite image, gradually gets poorer than the optimum No. 1. In series 4 the optimum itself is not distinct. This is on account of the fact that the aperture was so small that the main part of the diffraction pattern was not admitted. The subject of partial images will be discussed again in connection with Plate XII.

Series 1 of Plate XI shows eight optimum images represented by Nos. 1-8 inclusive, obtained with apertures of the sizes given in Table II.

TABLE II

No.	Aperture	Telescope
1.....	4 mm	48 in.
2.....	3	36
3.....	2	24
4.....	1.25	15
5.....	1	12
6.....	0.6	7.2
7.....	0.4	4.8
8.....	0.3	3.6

Series 2 is taken with the same apertures and under the same conditions except that the object O was illuminated with diffused light instead of monochromatic light. This was done by removing the point-source S (Fig. 1) and placing in its stead an incandescent light in front of which was a ground glass. This series represents, then, the actual telescope images.

Series 3, Plate XI, was taken with the same apertures as were used in series 1 and 2, but with reflected light. To accomplish this a white cardboard was placed just back of object O and directly against the wires. Four incandescent lights were then placed in front and a little to one side of the object. The lens L_2 was removed while this series was being taken, so that the illumination on the object would be more intense. Nos. 7 and 8 are missing in series 3,



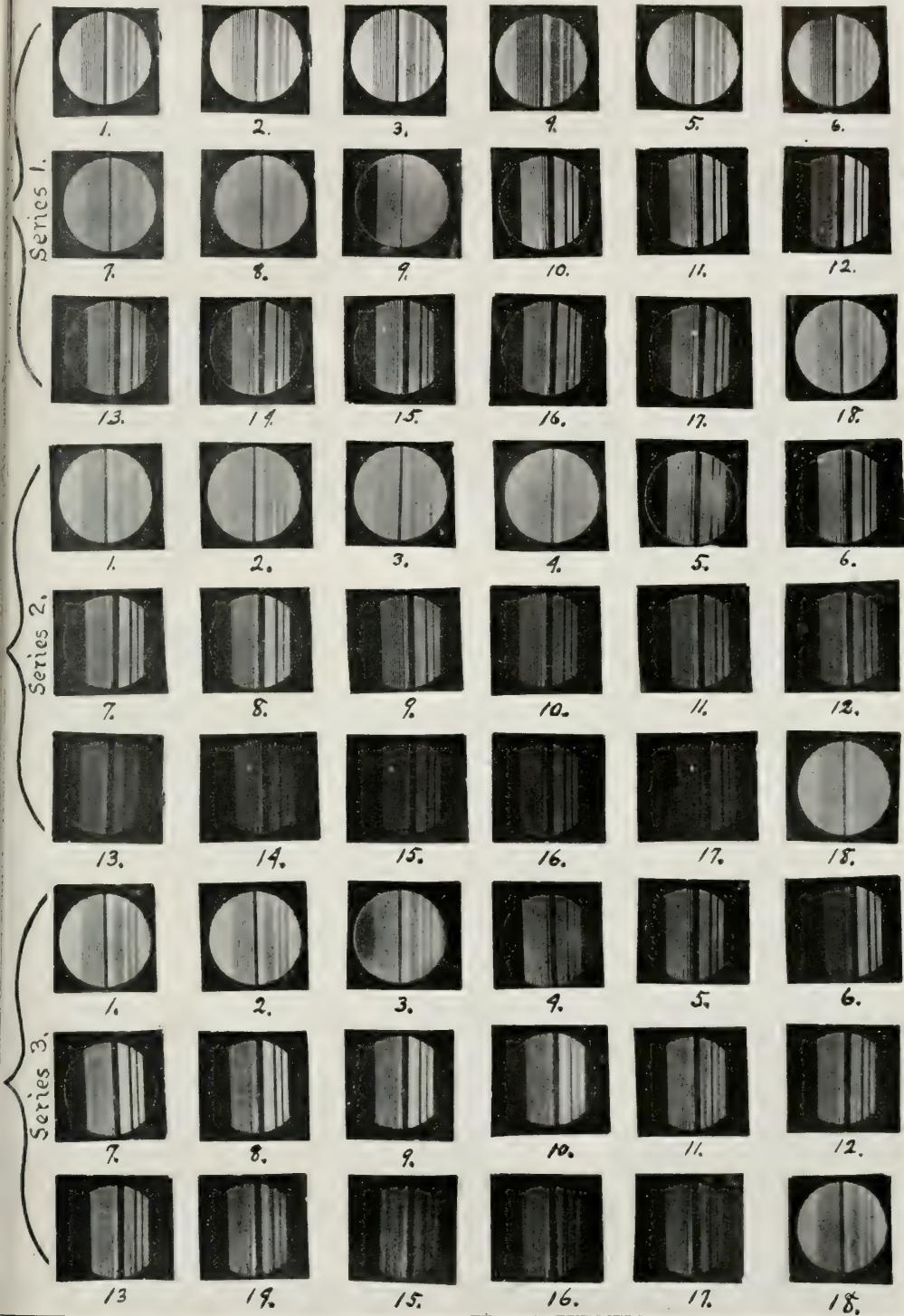
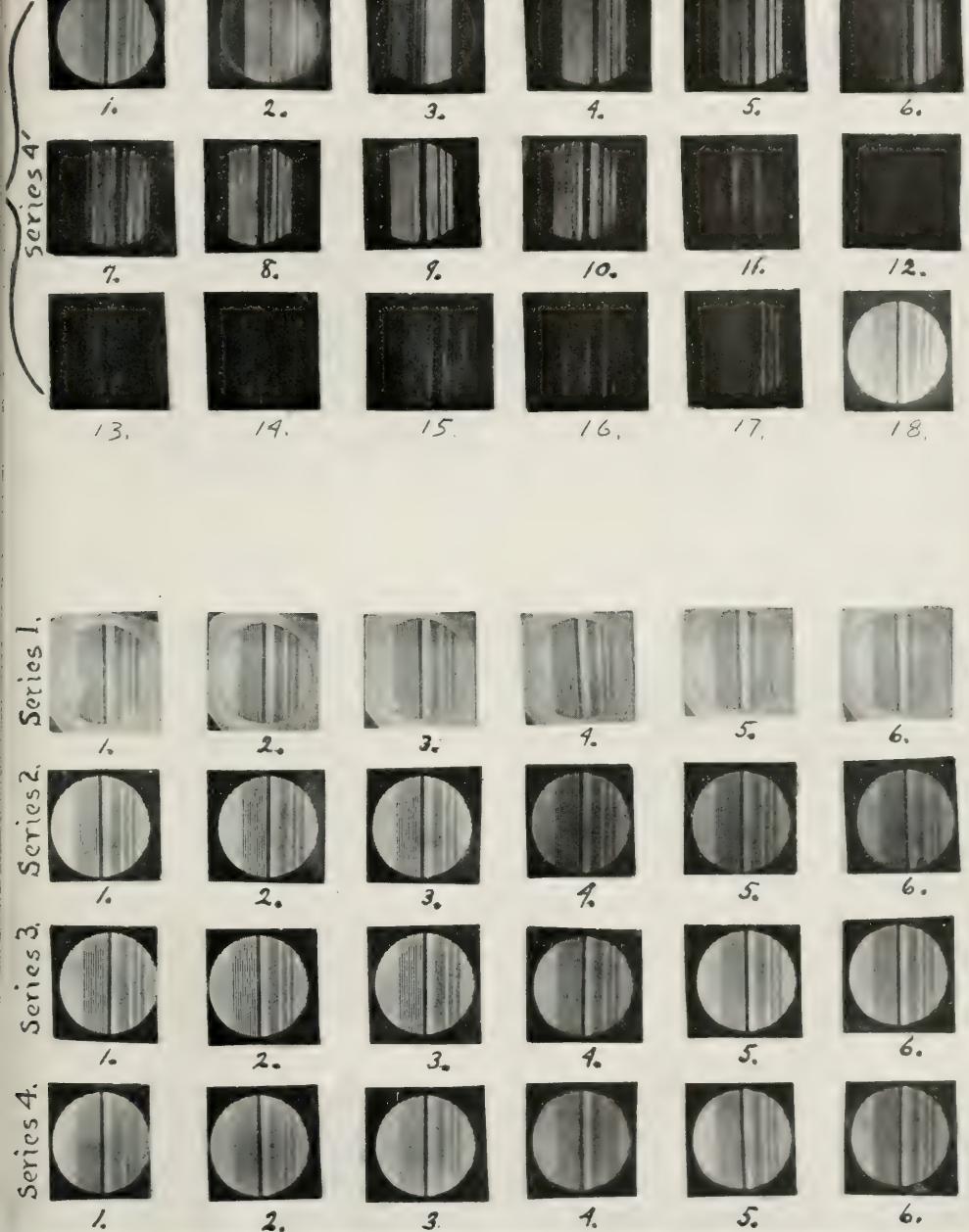


PLATE XIII





because the illumination could not be made intense enough to affect the photographic plate within a reasonable time.

The points to be noticed in comparing number with like number in these three series are as follows: (1) With the exception of the cases of the very small apertures, the optimum images are better than the diffused light images. (2) There is very little difference between series 2 and series 3. The lines in series 3 are possibly a little broader, owing to the effect of shadows. This point will be discussed again in connection with Plate XIII. The similarity of series 2 and series 3 shows that we were justified in using Stoney's assumptions in the substitution of object No. 2 for object No. 1.

Realizing that I was dealing with ideal atmospheric conditions I arranged for disturbing the atmosphere while an exposure was being made. To accomplish this, two bunsen burners were placed between the object *O* and the camera *C*. I do not claim that this gave real atmospheric conditions, but it is quite evident that there would be some similarity between movements of the air in the laboratory and movements of the atmosphere when a telescope is being used in actual practice. Series 4 and 5, Plate XI, show the results obtained. Series 4 is made up of optimum images taken with the apertures used above, while series 5 was taken under the same conditions as series 4, except that the burners were lighted and the air was in motion. It is quite evident that motions or disturbances in the atmosphere affect the quality of the image. The final conclusions from these results will be left for the latter part of this paper.

Realizing that the results obtained by use of the complex object might be questioned, I constructed a more simple object and photographed it under the same conditions as the first. The second object used was a simple wire grating made by winding wire around two screws which were fastened in a frame. The screws were made with fifty threads to the inch. Wire of two sizes (0.15 mm and 0.37 mm) was wound upon these screws and soldered. The wire on one side was then cut away, and that which was left was tightened by turning two nuts in the frame. This grating was then placed in the position of the original object. The advantage in using the grating with vertical wires came from

the fact that its diffraction pattern consisted of a row of horizontal spectra, rather than confused and promiscuously scattered spectra, as was the condition in the case of the first object. As the camera aperture is moved to one side, nearly all of the diffraction pattern is admitted (a part at a time) into the camera. The composite photograph would be a truer representation of the actual image in this instance, for more of the pattern is used than in the series already discussed.

Plate XII contains three series, showing the different partial images obtained with apertures of varying diameters, the first one in each series representing the optimum image. Series 1 was taken with a 4-mm aperture, representing a 48-inch telescope; series 2 with a 2-mm aperture, representing a 24-inch telescope; series 3 with a 1-mm aperture, representing a 12-inch telescope; and series 4¹, Plate XIII, with a 0.6-mm aperture, representing a 7.2-inch telescope. It will be noticed in series 1 that as the aperture was moved sidewise across the field, one half-millimeter at a step, six good images were obtained, while series 2 contains four, series 3, two, and series 4¹, Plate XIII, only one. It would be expected, then, that the composite image would be much better in series 1 than in the other series, and this is what is observed when an examination is made of No. 18 in each series. In series 1, No. 18 is practically as distinct as the optimum No. 1. In series 4¹, Plate XIII, even the optimum No. 1 is indistinct. This would indicate that the aperture did not admit enough of the diffraction pattern to give a good image.

Plate XIII, lower half, shows the same effects as were shown by Plate XI. These photographs were taken with the following apertures: 4 mm, 3 mm, 2 mm, 1.25 mm, 1 mm, and 0.6 mm, representing respectively, the same sized telescopes as were mentioned in the previous tables. Series 1 was taken with reflected light, series 2 with transmitted diffused light, series 3 with light from a point-source which gives us optimum images, and series 4 was taken under the same conditions as in series 3, except that the atmosphere between the camera and the object was disturbed by means of two bunsen burners. There seems to be very little, if any, difference between series 1 and series 2. This again shows

that it makes no difference where the illumination is located and is a further vindication of Stoney's theory. The optimum images in series 3 are better than the corresponding images in series 1 and series 2. This is possibly more evident in Plate XIII than in Plate XI. Series 4 shows conclusively that movements in the atmosphere affect the quality of the image to a marked degree.

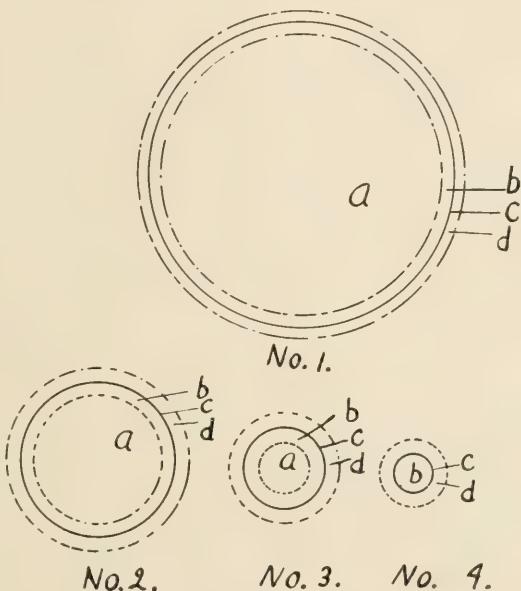


FIG. 2

In order to add clearness to the subject of partial images and further to explain the conclusions drawn from the photographs, Fig. 2 is inserted. The full line in these drawings indicates the relative size of the different apertures used. No. 1 represents a 48-inch, No. 2 a 24-inch, No. 3 a 12-inch, and No. 4 a 6-inch telescope.

The radii of the dotted circle are so chosen that the difference between each of these radii and the radius of the full circle would be equal to the relative radius of the fifth bright ring from the diffraction pattern of Mars. We can consider, then, that these three circles divide the space in and around the telescope objective

into three parts or divisions, *a*, *b*, and *d*. We then see that if the central bright spot of any of the infinite number of diffraction patterns from Mars falls within the space *a*, a good image will be formed. If the central bright spot falls within the space *b*, an image will be formed which will not be quite as good as those found in class *a*. As the central bright spot of the diffraction pattern passes over the edge of the telescope another class of images will be formed which will be much poorer than those of either class *a* or class *b*. This group of images is called class *c*. This corresponds to what has already been said in the previous paragraphs. If the central bright spot is not admitted into the camera, a very poor partial image is formed by the parts of the pattern that are admitted. As the central bright spot falls within the space *d*, only the outer diffraction rings enter the telescope and the images formed by them are poorer than those in either of the other classes. If the central bright spot falls outside of the space *d*, the essential parts of the pattern do not enter the telescope, and so we are not interested in them.

As has already been shown, the image formed in a telescope is the result of the superposition of the images from these four classes. If class *a* predominates the resultant image should be a comparatively good one, while if the poorer or inferior classes predominate, the resultant image will be of an inferior quality and thus will be indistinct.

By finding the areas of the different sections in each of the drawings of Fig. 2 some interesting comparisons can be made. Table III shows the relative values.

Now if we remember that the images formed by class *b* are fairly good partials and that those formed by class *a* are optimum partials, we can make use of Table III. When a 48-inch telescope is used, 75 per cent of the partial images making up the actual image are found in class *a*, while 86 per cent of the total are included in classes *a* and *b*. This would indicate that a 48-inch telescope should give a very good image of the disk of the planet Mars. These calculations are, of course, based on the image of the disk of Mars. The excellence of the image of the smaller details of the planet will be dependent on the relative size of these details as

compared with the size of the disk of the planet. No. 2 shows that when a 24-inch telescope is used, 56 per cent of the partials that make up the image are included in class *a* and 75 per cent in classes *a* and *b*. When we remember that the light from class *a* and class *b* is more intense than that from the other classes, we might

TABLE III

No.	Area sec. <i>a</i>	Area sec. <i>b</i>	Area sec. <i>d</i>	Area total	Area <i>a+b</i>
1.....	435	65	78	578	500
2.....	93	32	40	165	125
3.....	16	15	20	51	31
4.....	1.5	6.3	11	20.8	7.8

	Per cent <i>a</i> is of total area	Per cent <i>a+b</i> is of total area
1.....	75	86
2.....	56	75
3.....	31	60
4.....	7	37

expect a 24-inch telescope to give a reasonably good image. Nos. 3 and 4 indicate how far the quality of the image falls off when a 12-inch or a 6-inch telescope is used. In the latter case the aperture is so small that nearly all of class *a* is excluded. This is also in accord with experimental results, for it is found that when the aperture would not admit the whole of the bright part of the diffraction pattern, the image obtained was very indistinct.

CONCLUSIONS

1. The assumptions made at the beginning of this paper have been proved to be correct. This is first shown in Plates X and XI and later by Plates XII and XIII. There seems to be no difference between the photographs taken with transmitted diffused light and with reflected light. The sum of the partial images gives a composite image which seems to be of the same quality and shows the same details as the images obtained with diffused light. This point is of great importance because it shows that the resolution of the image into its different partials is permissible. It also shows that

the introduction of the lens in front of the object did not alter the optical conditions. If there is any difference between the composite image and the diffused light image, it may be accounted for by recalling that the composite image was taken with light of one wave-length, while white light was used when the diffused light images were obtained.

2. In order to obtain a good image the aperture of the telescope must admit all of the brighter parts of the diffraction pattern from the object. The essential part of the pattern would usually consist of the central bright spot and the first five or six bright rings. This conclusion is based on series 4, Plate XI, and series 3, Plate XIII. No. 6 in each of these series shows the effect of using an aperture that would not admit all of the brighter parts of the pattern.

3. Airy's formula can be used in making an estimate of the size of a telescope necessary to give a distinct image of a heavenly body. This is shown particularly in Fig. 2. The calculations and estimates made by use of this formula agree quite closely with the experimental results.

4. The quality of the image is not greatly improved by increasing the size of the telescope aperture indefinitely. Smaller details may be seen, however, with the larger telescopes. This is shown especially in series 3, Plate XIII. It will be observed that Nos. 1 and 2 are equally good. No. 1 was taken with a 4-mm aperture and No. 2 with a 3-mm aperture. No. 1, however, might have been able to show details that would not appear in No. 2, if smaller details had been present in the object.

5. Under ordinary conditions in nature, perfect images are not obtained. It has been shown that better images can be obtained with this experimental apparatus than can be obtained under normal conditions. In every case it was found that when an aperture large enough to admit the essential parts of the diffraction pattern was used the optimum images were better than those secured by the use of diffused light. This is shown in Plates XI and XIII.

6. If atmospheric conditions were perfect, details as small as 7 miles across, on the planet Mars, could be detected with a 24-inch telescope. This seems to be in agreement with the conclusions of Professor Lowell. He has detected certain details upon the sur-

face of the planet as readily with his 24-inch telescope as a number of other astronomers have seen with the larger instruments. This was due, not only to the undeniably good atmospheric conditions found in Arizona, but also, in accordance with the results of this paper, to the fact that his telescope is sufficiently large for these details. Whether these details represent canals or not is outside the scope of this paper.

7. Movements in the atmosphere affect the quality of the image to a marked degree. While real atmospheric conditions were not produced in the laboratory, yet the results obtained can be relied on to a certain extent.

PRACTICAL APPLICATIONS OF EXPERIMENTAL APPARATUS

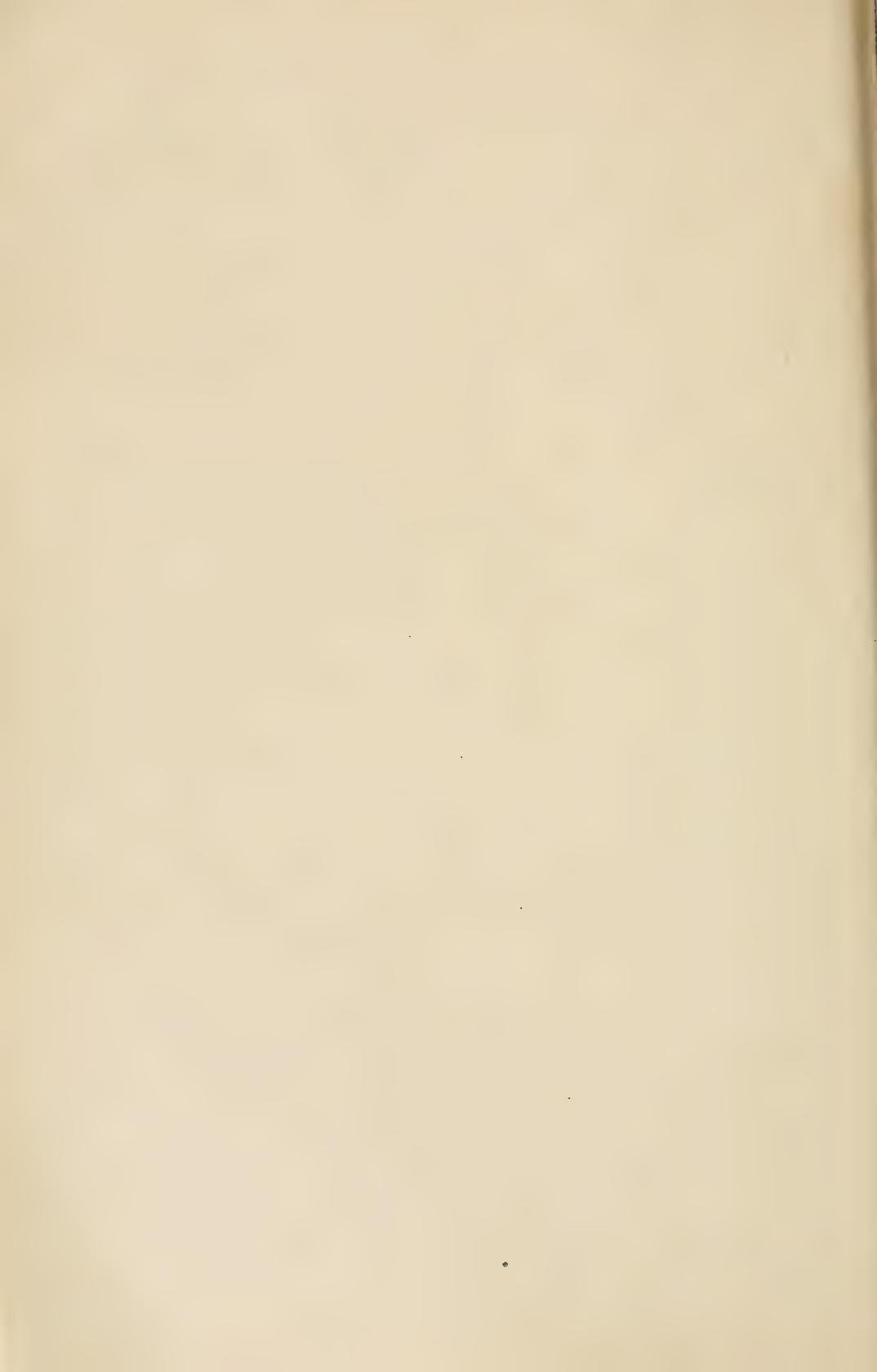
1. The apparatus as set up in this experiment can be used in obtaining a photograph of any transparent object, such as lines on a glass plate. A better photograph can be obtained in this way than can be secured in the ordinary way with diffused light for illumination.

2. This apparatus can be used in studying the partial images from any transparent body and the contribution of each of these to the total image formed naturally with diffused light.

3. As advocated by Stoney and as shown in the results obtained in this paper, this apparatus can be used as a practical check on the work of astronomers, and, in fact, on any persons who view or photograph distant or minute objects.

In conclusion I wish to acknowledge indebtedness to the staff of the physical laboratory of the State University of Iowa for their interest in the work, and, especially to Professor L. P. Sieg for suggesting the problem.

PHYSICAL LABORATORY
STATE UNIVERSITY OF IOWA
June 1914



WAVE-LENGTH-SENSIBILITY CURVES FOR LIGHT SENSITIVE SELENIUM AND THEIR SIGNIFICANCE.

BY F. C. BROWN AND L. P. SIEG.

IN our last paper¹ we showed that the sensibility curves for one of Giltay's cells was distinct and different from any that had been obtained by other investigators. Since then we have investigated a number of light-sensitive varieties made by Giltay, Ruhmer, Dieterich, and ourselves, and have found the interesting result that selenium as such does not have a characteristic sensibility curve. Such results will be set forth in this paper. Further we shall allude to the fact that the magnitude and position of the maxima of sensibility in the spectrum can be controlled by the treatment of the selenium in the process of making. Incidentally it will be shown that there is an interesting correlation between the change of resistance and intensity of illumination for short exposures no matter what the characteristic curve may be. Lastly we shall indicate the bearing of our results upon the theory of light-action in selenium.

GENERAL CONSIDERATIONS.

The phenomena of light action in selenium are almost unique, and it is for this reason that we should expect any theory of value to incorporate all the diverse phenomena that appear in this element. Of course we shall ultimately wish to explain the conductivity as well as the structure of selenium on the basis of the electron theory. Thus far an analysis reveals that any electron theory that is based on a single type of curve of sensibility is doomed to failure. And as a corollary to this we may say that any electron theory that presupposes only one light sensitive constituent in the selenium is also doomed to failure. For an analysis of exposure and recovery curves for a number of specimens of selenium has revealed that there are at least three components in selenium, at least two of which are acted upon by the light. The results of this paper are quite in agreement with such a complex structure of selenium, although we can not devise the necessary assumptions to determine if the three components are sufficient.

¹ PHYS. REV., N. S., Vol. 2, p. 487, 1903.

Mr. E. O. Dieterich¹ has been led by his researches in this laboratory to believe that the differences in the characteristics of light-sensitive selenium are purely the result of different crystal formations. His argument is very direct and will be presented as soon as his data are completed. Also it may be mentioned that we have produced two new crystal forms of very large size by subliming selenium at the same temperatures at which selenium cells are annealed. This makes it reasonable to assume that these same crystals with perhaps others also are in a more or less stable condition mixed together in light-sensitive selenium.

It is of little avail to select a single sample of selenium made by a particular treatment of the selenium, for the purpose of deducing the nature of light action, because all samples of light-sensitive selenium contain a mixture of certain components, some or all of which may bear direct relations to crystal formations. Any particular pressure, temperature, or time treatment only alters the relative amounts of the components present.

APPARATUS AND METHOD OF MEASUREMENT.

Apparatus.—The general method described in our former paper² was followed. The apparatus was improved by the substitution of a Hilger monochromatic illuminator in place of the one by Spindler and Hoyer. In the Hilger apparatus the lenses were 32 mm. or $f/5.6$ in diameter, as compared with the $f/12.7$ of the Spindler and Hoyer apparatus. We were thus able to augment our energy with a given slit width by approximately 5 times. As in the former work the source of light was a Nernst filament kept at practically constant intensity by supplying it with current from storage cells. The filament, while designed for use with 110 volts, was over-volted to about 120 volts, in order to increase the intrinsic brilliancy. The image of the glower was focused upon the first slit of the monochromatic illuminator. In front of this slit was placed a sectored disc, and an optical wedge, either of which, or both could be used to reduce the intensity of the light. The bundle of quasi-homogeneous light coming from the second slit of the illuminator (this slit was kept of the same width as the first one, usually about 0.7 mm.) fell upon a concave silvered mirror. This latter, together with the thermopile, and the selenium cell, was located in a light-tight box. This mirror could be rotated from without, so as to throw the focused image of the slit upon either the thermopile or the selenium. If it was desired to

¹ This work has just been completed and will soon be published.

² Loc. cit.

cover the whole cell with diffused light, the cell had merely to be drawn out of focus. Thin glass plates of the same thickness covered the thermopile and the selenium cell.

The thermopile, of the linear Rubens type, was one of the new series-parallel instruments of Bi with an alloy of Bi and Sn, made by Dr. W. W. Coblenz.¹ Its resistance was 2.25 ohms. The galvanometer used with the thermopile was of the Thomson type, made by Siemens and Halske. With its coils in parallel its resistance was 1.35 ohms. The sensibility depended of course upon the period, and with a period of about 6 sec., which we usually employed, its sensibility was about 5×10^{-10} amp. With this thermopile-galvanometer arrangement, a deflection of 1 mm. was obtained on a scale at a distance of 125 cm. when an incident energy of 4.4×10^{-8} watts/mm.² covered the thermopile strip. This latter determination was made with a calibrated carbon lamp at a distance of 2 meters, in accordance with the instructions in the certificate of the Bureau of Standards. In our experiment the area of the focused image of the slit was only 1/7 the area of the thermopile strip. Hence a deflection of 1 mm. in our actual experiments indicated an energy of 7×4.4 or 30.8×10^{-8} watts/mm.² upon the thermopile, and hence upon the selenium cell.²

One other device should be described. This was the arrangement by which we could expose the selenium cell at a certain moment, and then throw in the galvanometer for a certain short time. The same device that opened the shutter from in front of the Nernst glower, operated a trigger that released a pendulum. As this pendulum started moving it removed a shutter, thus exposing the cell. As soon as desirable after this operation (usually at once) a key was thrown by this same pendulum thus connecting a galvanometer in circuit. At a certain time later a second key was tripped, disconnecting the galvanometer. The change of resistance could thus be determined by the galvanometer throw for a short interval and at any reasonable time after the exposure of the selenium. The selenium was placed in one arm of the Wheatstone bridge, in which various E.M.F.'s were used. In some cases long exposures were made, but unless otherwise indicated our curves are for mean exposures of 0.4 seconds. In either the long or short exposures we employed the same galvanometer described in our previous paper.

¹ PHYS. REV., N. S., III., p. 59, 1914.

² A correction should be made to the footnote of our previous paper, Vol. II., p. 489. While a deflection of 1 mm. meant an energy of 9.3×10^{-8} watts/mm.²; using the total area of the thermopile, the area of the image of the slit was, in this case, about 1/6 of that of the thermopile strip. Then in our previous experiments 1 mm. deflection corresponded to 6×9.3 , or 55.8×10^{-8} watts/mm.² upon the thermopile, and hence upon the selenium. So our present arrangement is approximately twice as sensitive as was the former.

As in our previous work, care was taken to adjust for equal energy throughout the observations for each curve. Possibly equal energy is not the proper basis upon which to compare light actions, but at any rate it is the most definite and fundamental basis upon which to work. While equal energies were obtained as determined by the thermopile, the question might nevertheless be raised as to whether equal values of the energy penetrated and acted upon the selenium. If the selenium were selectively reflecting this would be a serious source of uncertainty. However, in connection with a separate investigation we measured the amount of energy reflected from the surface of the selenium in a typical cell for which we determined the characteristic curve and we found that for each wave-length the total reflected energy was only a little more than one one hundredth of that incident of the selenium. Thus it appears that a selenium cell is a fairly good black body. We shall deal with the optical properties of selenium in a separate paper.

Effect of Varying Slit Width.—As is well known, the beam of light from

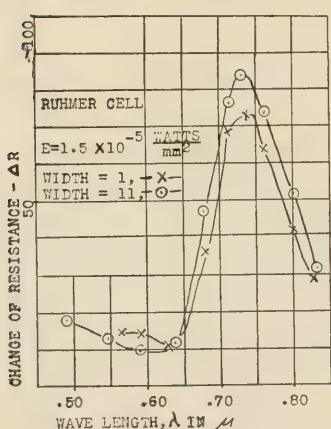


Fig. 1.

a monochromatic illuminator is only a quasi-homogeneous beam, and its non-homogeneous character becomes more and more evident as the red end of the spectrum is approached. Any curves for such an apparatus can be corrected with considerable definiteness¹ for the slit width, although the calculation is rather a laborious one. In view of the labor involved in the calculation, it was thought best to try first an experiment to test the extent of the inaccuracy that arises from the use of a finite slit width.

Fig. 1 represents the results of this experiment. The two curves are clearly indicated in the figure, the one for a very narrow slit with (about .14 mm. on both the collimating and focusing telescope) and the other for the unusual slit width of about 1.5 mm. The slit width was thus varied by about a factor of eleven. By means of the rotating sector the energy intensity was lessened to correspond to that of the narrow slit, thus giving the same change of conductivity in the selenium at wavelength $\lambda = .64 \mu$. There is no special significance to be attached to the slight variation of the magnitude of the maximum. It merely indicates that there are small outstanding errors that nullify any necessity for

¹ Paschen, Ann. d. Phys., 60, 712, 1897.

making slit width corrections. Having justified the use of such a wide slit width, we believe ourselves perfectly secure in our results which were usually obtained with slit widths of 7 mm. This gave us a maximum of energy with a negligible error from spectral impurity.

Effect of the Order of Exposure.—Thinking that the shape of the curves might vary slightly with the order of exposure to the light of varying periodicity, an experiment was tried the results of which are shown in Fig. 2. First a curve was taken for a Ruhmer cell by the usual procedure, *i. e.*, by measuring the sensibility at the shortest wave-length first and then proceeding step by step to the reading for the longest wave-length. Then this procedure was exactly reversed by taking the sensibility for the longest wave-length first and going backward. We concluded from these curves and a number of other cases where it was advisable to check readings that the order of exposure made no material difference. However, a little greater reliability was attached to the first order of exposure. The curves given in this paper are substantially correct. After readjusting our apparatus and replacing some of the cells, we were able to duplicate results with surprising accuracy.

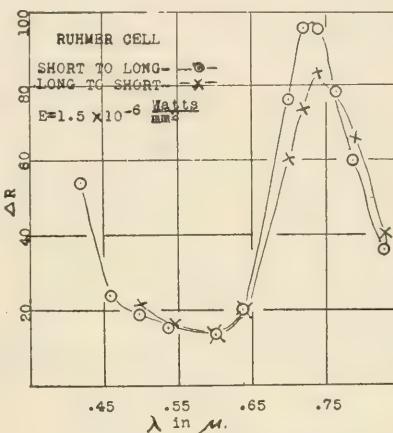


Fig. 2.

THE CHARACTER OF THE SENSIBILITY CURVES.

General.—When this work was begun it was believed that sensibility-wave-length curves obtained by using short exposures should for all varieties of selenium show the same characteristics, providing that the rapid changes in selenium always arise from a common light-action on one component of the selenium. Or conversely it was believed that the sensibility curves should be complex, providing that the rapid changes in the selenium by light arise from action on two or more components of the selenium with widely varying rates. It is the converse view that naturally suggests itself following the analysis made by one of the authors.¹

Fig. 3 shows the various types of sensibility curves which we have obtained with different samples of selenium, and we do not claim to have exhausted the list. The observed changes of resistance recorded on each

¹ PHYS. REV., 33, p. 403, 1911.

curve were taken for exposures of equal intensity, wherever we found that the form of the curve was materially affected by change of energy. The scales for each curve are however arbitrarily chosen, so that the maximum ordinate of each curve lies at about the value 100. Thus the curves serve a purpose resembling a spectrum analysis of an element.

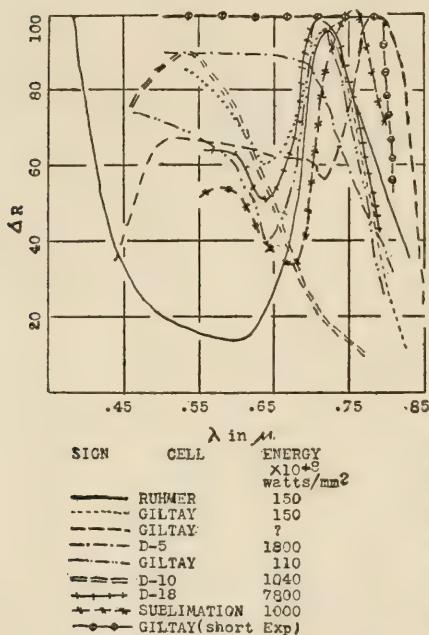


Fig. 3.

both by Pfund¹ and ourselves.² Only two of the curves in Fig. 3 showed such a variation. In some instances tests showed the character to be only imperceptibly changed by intensity variations of the ratio of 50 to 1. Furthermore we found that the character of the curves was not necessarily much affected by the duration of exposure. Only two of the eight samples, whose curves we are discussing, showed such large variations. This also is new.

It is obvious that there is no characteristic curve to be found by the method of procedure that we followed. A Ruhmer cell in vacuum indicated a maximum in the ultra-violet too far out for us to locate, and another maximum at $.72\ \mu$. This selenium had a broad minimum extending from $.55\ \mu$ to $.62\ \mu$. Recently Mr. Dieterich has succeeded in producing two samples of selenium with a maximum near the ultra-

¹ PHYS. REV., 34, p. 370, 1912.

² Loc. cit.

The intensity of the lines can be compared with the lines of the same spectrum in order to establish the character of the unknown. In spectrum analysis the amount and the temperature of the element producing the spectrum are matters of secondary importance. Just so the curves in Fig. 3 are characteristic curves, but they neglect to bring out the absolute or even the relative sensibility of the different samples of selenium. The chart accompanying the curves gives the names of the types of cells used and also the energy intensity that resulted in the indicated curves. However it is rather unusual for the character of the curves to change with varying intensity such as had been previously observed

violet. But with these exceptions all samples which have come to our notice decrease more or less precipitously in their sensibility back of $.5\mu$. Many specimens have the indicated maxima at about $.7\mu$, but this maximum wanders all along to $.8\mu$, and in the typical Dietrich cell, as indicated in our paper by the letter *D*, this maximum dwindles or disappears altogether. Stated briefly the maximum that so frequently appears in the red, may be controlled both as to its location and its magnitude even to its disappearance. One cell has shown considerable sensibility out as far as $.85\mu$. Similarly as regards the minimum, which usually occurred about $.64\mu$. In the Ruhmer cell it occurred back as far as $.6\mu$ and in the selenium whose crystals were deposited by sublimation in a high vacuum, it occurred at $.68\mu$ and in one other cell at even longer wave-lengths. In one of Giltay's cells and also in one of Mr. Dieterich's cells, the fourth and ninth curves respectively in the chart, the minimum did not appear at all. At about $.55\mu$ there was usually a broad maximum but it is observed that this region may contain a broad minimum as well.

Without any further work the conclusion seems obvious that light produces more than one action in the selenium, or in other words there is more than one component or kind of selenium if you please existent simultaneously in the selenium cell.

The Giltay and Dieterich Types.—While it is true that both Giltay and Dieterich do make cells of widely varying character, it is nevertheless true that all of Giltay's cells of which we have any knowledge have a pronounced maximum at $.69\mu$ or beyond and a more or less well-defined one in the region of $.55\mu$. On the other hand Dieterich's samples usually have a very pronounced maximum about $.55\mu$, and a controllable maximum in the red which may be entirely eliminated by the method of making. This so called Dieterich type is shown by curve *D*, Fig. 4, where the energy intensity was 6.6×10^{-6} watts per mm.² For greater or less illumination intensity, the character of the curve was as far as we could determine identical to this one. In the same figure, the curves *G*₁ and *G*₁' are for a typical Giltay cell, where the intensity of illumination varied by a factor of 20 to 1. It is common for the Giltay cells to maintain the same character unaltered for widely varying intensities, just as these curves indicate.

The Effect of Varying Electrical Intensity.—Since it has seemed advisable to regard the selenium as in a state of equilibrium under the action of a number of forces, it is reasonable to expect that an alteration of any one of these forces might alter the form of the sensibility curve. We have yet to test this point particularly for the varying temperature conditions. An examination of the voltage effect shows that the char-

acter of the curve is only slightly altered, while the sensibility is uniformly and materially altered in magnitude. The curve in Fig. 5 indicated by circles shows the characteristic curve of cell D₇ for an intensity of 0.1×10^{-5} watts per mm.², when exposed for 30 seconds. There was a potential difference of 3.5 volts across the selenium. Next this was changed to 0.5 volts and the intensity altered till it produced the same change of resistance at $.45 \mu$ as was produced with less intensity and

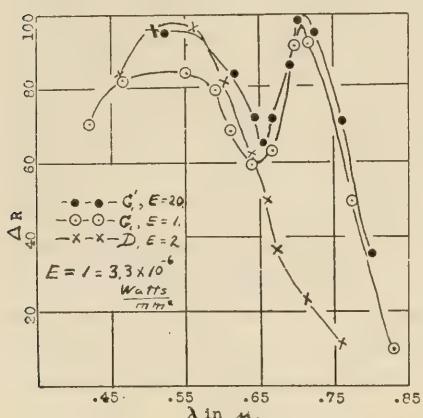


Fig. 4.

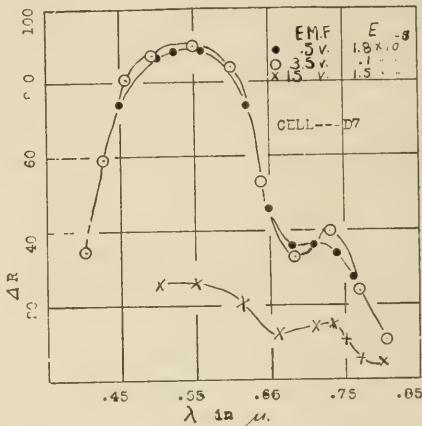


Fig. 5.

greater potential. With this intensity which was 18 times greater the curve indicated by solid dots was obtained. It is to be noted that altering the intensity by a factor of 18 to 1 had the same effect as altering the potential by a factor 7 to 1. However it must also be noted that while the deflections were nearly identical for the sake of comparison, that the absolute change of resistance was only about one seventh in the second case of what it was in the former.

It may be estimated that a change of potential of the order of 50 to 1 will so balance the selenium in this cell that the same absolute change of resistance would be produced when the intensity of illumination is varied by a ratio of 18 to 1. The conclusion is that for this cell the alteration of the electric intensity alters the character of the curve only slightly, but that it makes a large difference in the absolute change of resistance by light. This last point has also been verified in former papers. The lower curve in the figure is for short exposures, and with 15 volts across the selenium. Thus changing the duration of exposure, the electrical intensity and the light intensity does not alter the character of the curves to any definite and marked degree in this particular cell.

The Maxima are Inherent in the Selenium.—Since the well-known

experiments of Pfund and Berndt no one has questioned that at least a great part if not all the light sensitiveness of selenium is in the selenium structure itself and not because of some impurity or selenium compound. Yet when different samples show such widely varying characteristics, the question may well be raised again as to whether impurities do not play an important rôle in prescribing the characteristics. Mr. Dieterich is obtaining a large amount of evidence to prove that impurities are of very secondary importance if they enter at all. One point that may be mentioned is illustrated in Fig. 6. He took a Giltay cell marked "normal G" and subjected it to purely physical treatment, after which the characteristic curves were of the form indicated by curves E_1 and E_{10} , where the illumination intensity varied by a factor of ten. By this treatment which he will relate in detail, the Giltay cell was transformed into a Dieterich cell. It is also worthy of note that the character of the curves was unchanged by a variation of the intensity by a factor of ten. As has been previously pointed out, the selenium components seem to be put in a dynamic equilibrium in the process of making the cell under the action of a number of forces such as heat, and pressure treatment, and further, these components are maintained in equilibrium under a number of forces such as pressure, temperature, illumination, absorbed materials, electrical stress and the crystal formation itself.

That the characteristics of any given specimen are inherent in the selenium itself is yet further verified by the fact that the maximum in the red can be put in or eliminated at will by the heat treatment. And it is expected that the exact conditions will soon be discovered which determine the presence or absence of the maxima in the shorter wavelengths of the visible spectrum and even in the ultra violet. The curves in Fig. 7 are taken from Mr. Dieterich's samples. The remarkable difference in these curves arose solely from the difference in heat treatment during the process of making. In fact he can predict almost without failure what will be the character of a given sample of light-sensitive selenium. It should be noted that the intensity of illumination was the same for all curves in Fig. 7.

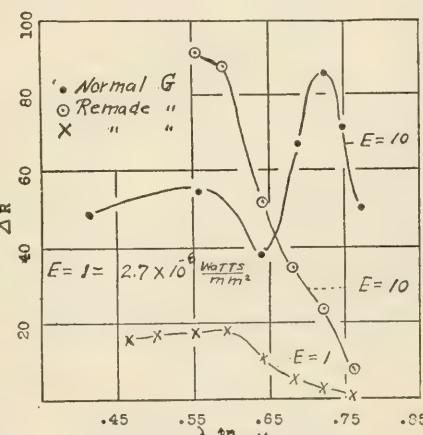


Fig. 6.

The Variation of the Sensibility.—Generally the light sensibility of selenium is regarded as a function of the amount of selenium that has been transferred from the amorphous to the crystalline state. And yet it seems perfectly futile to attempt to explain the enormous variations in sensibility on this basis. The variations so greatly outnumber the possible combinations. Mr. Dietrich has been able to vary the sensibility over a very wide range without altering the character of the sensibility curve, but there seem to be a number of factors entering into the exact control, only a part of which he is aware of. Nevertheless

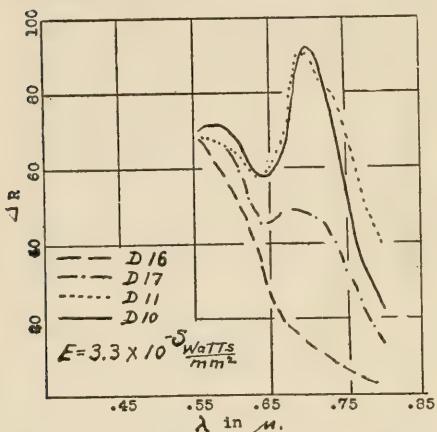


Fig. 7.

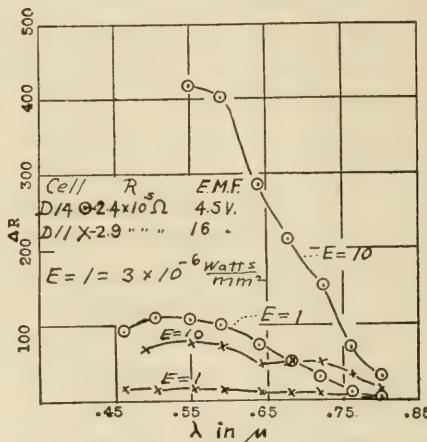


Fig. 8.

he has produced a low resistance cell which shows an effective sensibility at $.59\text{ }\mu$ about ten times greater than that of any Giltay cell in our possession. Its character is shown by the curve $D14$, Fig. 8, for two intensities varying by ten to one. And again starting with a sample of the same amorphous selenium and proceeding differently with the treatment he produced a cell $D11$ which had about the same specific resistance in the dark and only a slightly different characteristic curve, but its sensibility as can be learned from the curves was only about one twentieth of that of cell $D14$. In making this deduction an allowance must be made for the lower voltage used with cell $D14$.

THE VARIATION OF SENSIBILITY WITH INTENSITY OF ILLUMINATION.

Quite recently Nicholson¹ has made a very able mathematical analysis of certain phenomena in selenium on the basis of one electron theory. Without discussing the reasonableness of his assumptions, it may be of interest to test some of his deduced equations over a wider range than

¹ PHYS. REV., N. S., Vol. 3, p. 1, 1914.

was done in his work. He used only two varieties of selenium and he was only prepared to take exposures as short as 12.5 seconds. In applying his results to his theory he presumed that an exposure of such duration was equivalent in its effect to an instantaneous exposure. We are inclined to doubt this presumption. Our results should have the advantage that comes from a study of a larger number of varieties of selenium and also the advantage of exposures of 0.4 second duration, which more nearly approximate instantaneous effects.

The most critical test of Nicholson's theory perhaps lies in the derived relation between the change of conductivity and the intensity of illumination. This relation is expressed by the equation,

$$d = D \cdot I^\beta,$$

where d is the change of conductivity, I is the intensity, and D and β are constants. According to Nicholson's theory β should have the value $\beta = 1/2$ for instantaneous exposures in the shorter wave lengths and $\beta = 1$ for the red and infra red, and $\beta = 1/2$ for unlimited exposures throughout the spectrum. The above equation was originally set up as an empirical equation by Pfund.¹ We find justification for the use of the equation when used as an empirical one and applied to any given cell, but we can not see that the simple assumptions regarding absorption, reflection and resonance as given in Nicholson's paper, are sufficient to

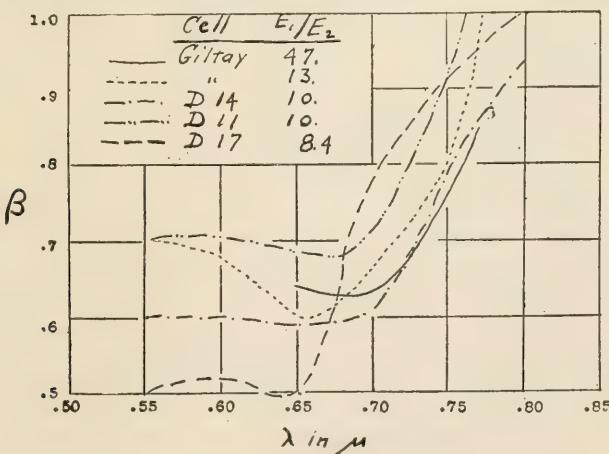


Fig. 9.

explain the varying values of β in the different samples of selenium, nor the variations in a given sample. It must be remembered that the constant β occurs as an exponent, and consequently small deviations in its

¹ PHYS. REV., Vol. 34, p. 370, 1912.

value are of relatively greater importance than relative errors in a multiplying or additive constant.

The manner in which β varies for exposures of 0.4 second for a number of different samples of selenium is shown in Fig. 9. It is rather interesting that cells which gave such widely varying characteristic curves (see Figs. 3, 7, and 8) should show such a general likeness in the variation of the constant β , for the different periodicities of light. It is observed then that β varies in a general way between .5 and 1 for short exposures.

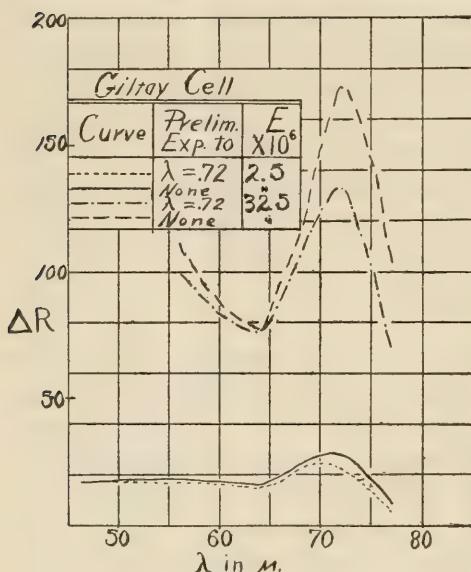


Fig. 10.

a preliminary exposure to a fixed quantity of energy from a beam of light of a given wave length. Nicholson made exposure tests similar

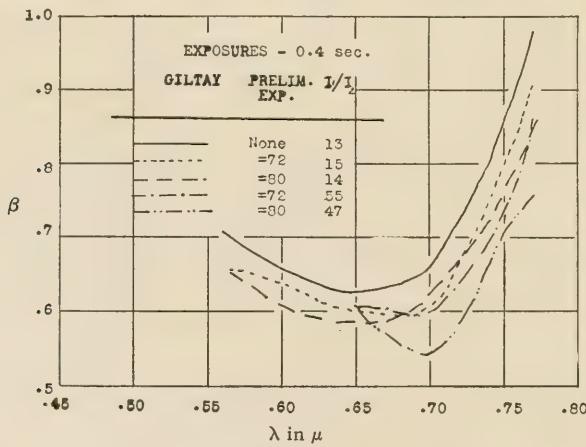


Fig. 11.

to this except that instead of making the additional exposure a preliminary one he left a steady exposure on the cell while he was

running a curve. In both cases the effect is much the same, and has the tendency to blot out the effects due to slow changes of resistance accompanying light-action. The effect of the preliminary exposure was slightly to iron out the maximum. However, the curves relating β and λ are not materially altered by the preliminary exposures. The first of these two results is shown in Fig. 10, connecting the change of resistance and wave-length; and the second point covering the variation of β and λ is shown in Fig. 11.

CONCLUSIONS.

The analysis made some time ago on the basis of the rates of change in the selenium, showed the structure of the selenium to be complex, consisting of three components in the specimens studied. Now we have made an analysis on an entirely different basis, that of the character of the sensibility curves, and our analysis reveals again a structure at least as complex as that revealed formerly by other samples of selenium. We are not yet able, however, in the latter analysis to set up a simple set of postulates whereby we can subject our analysis to a mathematical test as was done formerly. As far as can be seen our analysis requires at least two separate light actions in the selenium.

No doubt the action of light in any of the components is of such a nature that electrons are made free when one component changes to another, because the former analysis into several varieties of light sensitive selenium required that electrons be made free but in no case did it require the recombination of electrons. Knowing that the structure of light sensitive selenium is complex, and knowing what we do about the nature of this complexity we should now perhaps be in a position to apply the electron theory to an explanation of the phenomena.

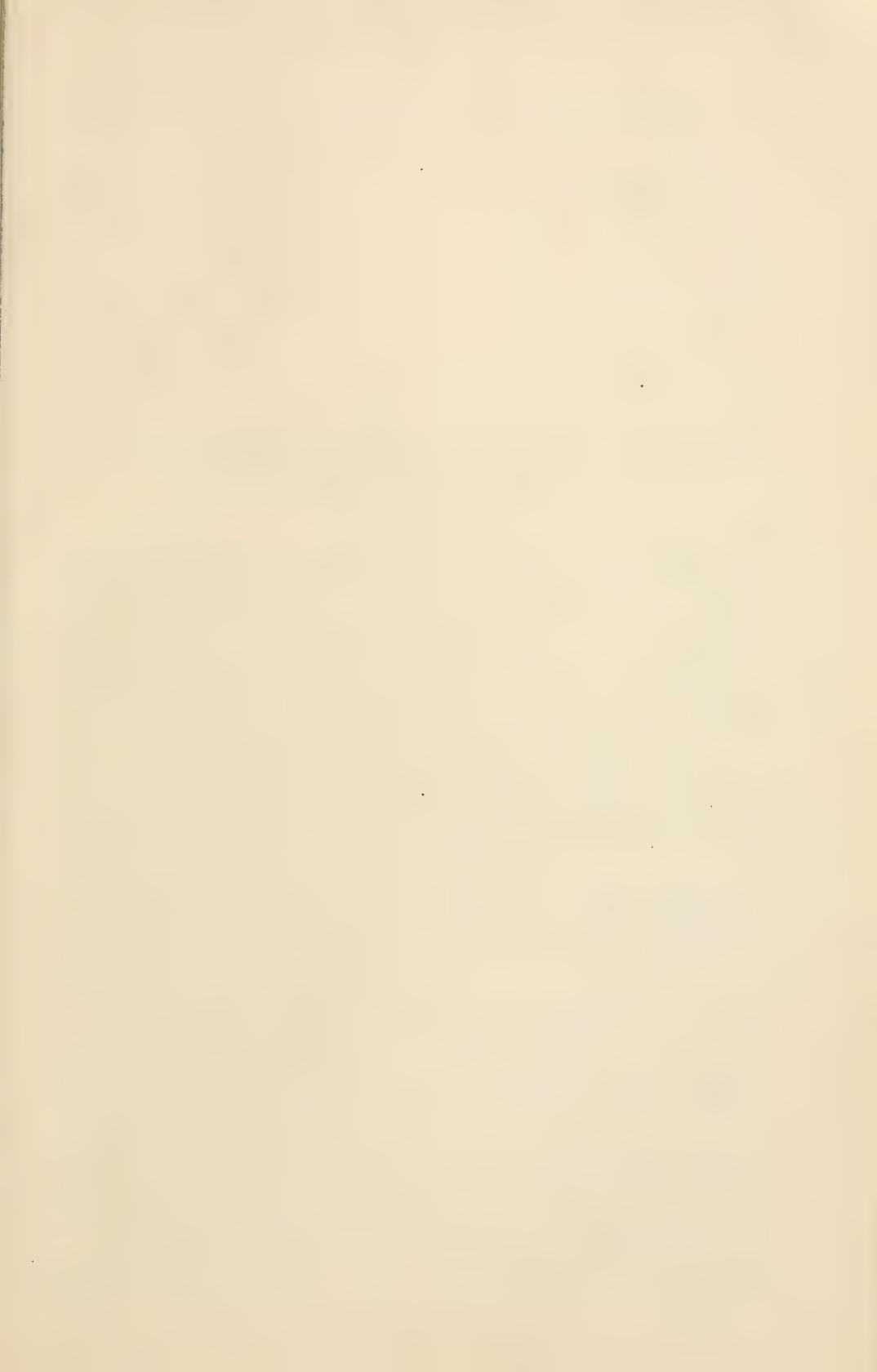
We have isolated a number of new crystal forms of selenium by sublimation of selenium in a high vacuum. The conditions which determine what kind of crystals will form must be very definite, for we have had very large crystals of different forms grow up within a millimeter distance of each other where the temperature and pressure could not have varied greatly. In free unhampered space some of these crystals have a length of more than ten millimeters. We know of four formations of crystal selenium that are doubly refracting when formed in a vacuum. Whether the crystals in the selenium cell are doubly refracting we are not quite sure, and yet one cell made by the formation of crystals directly from the vapor state must have contained some doubly refracting crystals. The point that we wish to make here is that crystals which are directive in their structure towards light should also be directive in their electrical

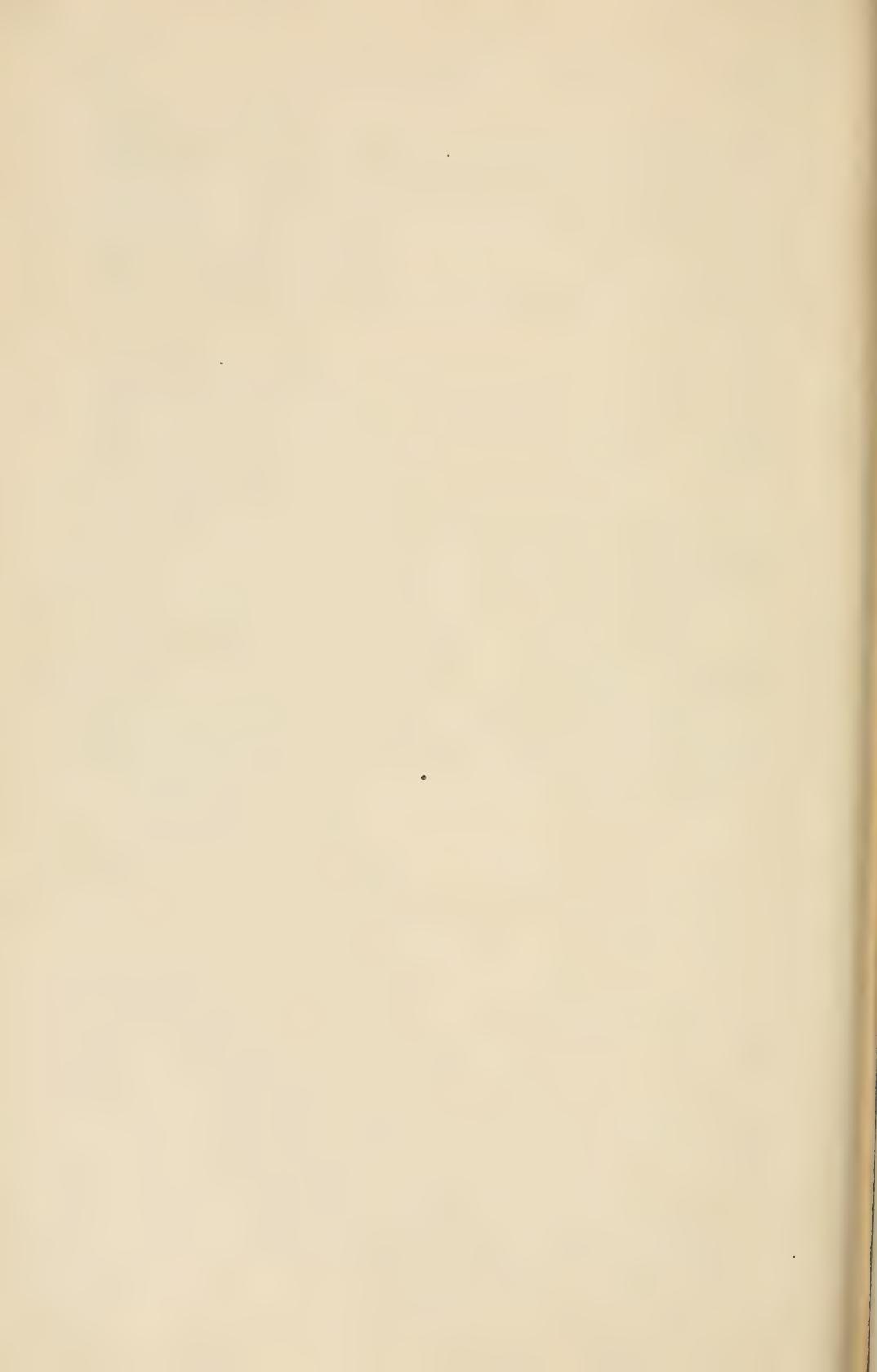
properties and if these crystals are instrumental in the conduction they should alter the conductivity differently depending upon their positions. If so we must in explaining the light sensitiveness of selenium allow for the formation of crystals either with axes pointed promiscuously or in consistently varying directions. Add to this a mixture of crystals in more or less stable equilibrium as to form and position and we have we believe a basis on which all the light electric properties of selenium may be worked out.

Previous results on the effect of abrasion¹ and on the pressure effect on the electrical conductivity indicated in a very marked degree that the slow changes accompanying light-action were the result of crystal changes. There was doubt concerning the seat of the rapid changes. It was conceded that perhaps light might expel electrons from the atoms in the transformation of one component to another. If in this present work we had found a single or slightly varying position of maximum spectral sensibility, we might have been justified in concluding with Pfund and others that the primary thing is the liberation of electrons from atoms of selenium. But if there is one significant conclusion that can be accepted as a result of the variation of the sensibility curves, it is that light does not act on the atoms as units. Rather a larger unit, no doubt of the order of a crystal unit, is the seat of the disturbance by light action. We are compelled to recognize crystal boundaries when dealing with the flow of electrons in selenium, possibly also in other elements. Otherwise there is no apparent basis for the unification of our knowledge.

THE PHYSICAL LABORATORY,
THE UNIVERSITY OF IOWA.

¹ Phys. Zeits., Nov. 15, 1912.





THE CRYSTAL FORMS OF METALLIC SELENIUM AND SOME OF THEIR PHYSICAL PROPERTIES.

BY F. C. BROWN.

WHETHER light-sensitive selenium is made up of homogeneous crystal structure or of complex units is of importance in explaining the nature of light action in selenium. Thus the author has been led into a study of the crystal forms of metallic selenium, which study has been particularly fruitful in that new crystal forms of very large size have been isolated. These crystals are of such a size that the optical and photoelectric properties of individual crystals can be studied. Thus we are able to eliminate some of possible causes of complexity in selenium, such as polymorphic crystal mixtures, unknown condition of crystal contacts, irregular placing of the crystals, and impurities. The fact that these new crystal forms are light-sensitive opens up a large field of investigation of which this paper is only preliminary.

Muthman¹ described only one crystal form of metallic selenium of the hexagonal rhombohedral system. These crystals were produced by the sublimation of the vapor of selenium in air and were never larger than 0.2×0.5 mm.

Saunders² also describes only one form. His conclusions were based upon the changes in volume accompanying temperature changes, as determined by dilatometric measurements. The difficulty with Saunders's method is that different crystal forms having identical or only slightly varying density could not be detected.

Marc³ following the experiments of Uljanin⁴ who observed two distinct crystallographic structures under the microscope, and following his own

¹ Zeit. f. Kryst., 17, 356, 1890.

² "The Allotropic Forms of Selenium," Journ. of Phys. Chem., Vol. 4, p. 423, 1900.

³ Die Physikalische Chemischen Eigenschaften des Metallisches Selens, Verlag von Voss, 1909.

⁴ Wied. Ann., 34, p. 241, 1888.

experiments on selenium cells, was led to believe in the existence of several forms of metallic selenium, which through the action of light underwent polymorphic transformations. By the investigations of the heat changes, the electrical conductivity and a microscopic investigation of the surface he was able to detect with certainty the existence of two polymorphic forms. The one form was crystallized by heating the selenium at lower temperatures in the neighborhood of 100° . It was essentially non conducting and was designated form *A*. At temperatures of 205° to 215° this selenium went over into selenium *B*, which was found to be quite conducting. A microscopic investigation showed the form *B* to be of uniformly round mounds, while that crystallized at 200° contained long crystals. The crystals observed however were only of the size of about 0.004 mm. Marc's results which led him to believe in the existence of two forms *A* and *B* and which led him to believe in the dynamic equilibrium of these forms, were not sufficient to convince him that there could not be other forms. One of the phases producing equilibrium he regarded as a vapor phase, thus giving only one solid form for two phases.

Recently White¹ did some very excellent work with selenium blocks crystallized at 200° . He found the interesting result that a greater change of conductivity was produced when the incident light was in the direction of flow of the current than when the illumination and electric current directions were at right angles to each other. He concluded that in the selenium block the highest resistance is at the electrode contacts and also that the greatest change of conductivity by illumination takes place at the electrodes. However in interpreting his results he did not consider the change of conductivity arising from increased potential gradient when the blocks were illuminated at the contact surfaces. He also observed a number of phenomena such as has been observed in the so-called selenium cells.² This work of White further suggests the advisability of obtaining single isolated crystals of selenium in which the physical conditions, may be known and controlled.

THE PRODUCTION OF ISOLATED CRYSTALS.

The new crystal forms that are the subject of discussion were in all cases produced by the sublimation of the vapor, either in a high vacuum or at atmospheric pressure. The vitreous selenium which it was desired to transform into crystals was placed in one end of a glass tube of 35 mm. inside diameter and of 30 to 60 cm. length. This glass tube fitted snugly

¹ Phil. Mag., Ser. VI., Vol. 27, p. 370, 1914.

² Unquestionably the term "selenium bridge" as he suggests is a better term than "selenium cells."

into a cylindrical electrical oven of 30 cm. length, of which one end was closed. Near the open end of the oven there was a rather large temperature gradient whether the tube was evacuated or not. All the selenium that deposited in any form was usually within a distance of less than 7 cm. along the tube. A current of about six amperes in the oven was sufficient to heat the selenium to be transformed to about 270° . The selenium was kept at this temperature for a period varying between one day and one week. But there was no temperature regulator and consequently there was considerable variation in the temperature during the day, with either the dynamo or the storage battery as a source of current. The selenium was allowed to sublime on the walls of the glass tube, on a thermometer bulb, or on a form with wire electrodes for a light-sensitive selenium bridge. It was hoped that the thermometer would register the temperature at which the crystals formed on it, but the temperature gradient was so large that no reliance was placed in the readings.

The result may be stated in a general way as follows. The largest crystals in every case were formed at the highest temperature at which the selenium sublimed in the closed tube. This temperature is believed to be above 210° . It should have been ascertained more accurately, but the effort was rather discouraging because of the absence of automatic temperature control. These crystals became smaller as the cooler portion of the tube was approached, until about 3 cm. back of the largest crystals there was a continuous sheath of selenium of a silver luster surrounding the inner wall of the tube. On some occasions the hotter edge of this sheath was fringed with small well-developed rhombohedral-hexagonal crystals (see Fig. 1) such as described by Muthman¹. Back of this silver-like sheath was sometimes discerned a rather black sheath which also had a metallic luster. Further along the tube at temperatures perhaps below 100° was usually a very thin deposit of red amorphous selenium. I was rather surprised to find so small an amount of selenium deposited in the red amorphous form, and so large a quantity in the metallic forms. I was also surprised in some cases to find so large a fraction of the selenium as one fifth of the total to be deposited in the form of large crystals. This is rather a sufficient argument against any view that might presuppose impurities to form the large crystals. The selenium that was placed in the tube to be sublimated was Merck's purified selenium.

Invariably the largest crystals were formed at the highest temperature, but it is not clear what determined the form they should take. The photograph in Fig. 2 shows distinctly varying formations that occurred

¹ Loc. cit.

in two separate tubes. The acicular crystals were sometimes 11 mm. long and not more than 0.2 mm. in any other dimension. Usually they developed a number together in a cactus-like growth, with from 3 to 20 spines starting from a common center. These spines or needles were quite stiff and tough, rough handling and even dropping very rarely injuring them. The needles of any given cluster were usually very much alike in size and appearance. They always had a metallic luster by reflected light. If fully developed there were six surfaces. And yet some entire clusters apparently developed with any number of surfaces less than six. Under the microscope these crystals seemed the least transparent of any that were produced.

The crystals of the second type shown in Fig. 2 were large flat crystals with parallel surfaces usually less than 0.3 mm. apart. The length of one of these crystals indicated in the photograph was 9 mm., and for the greater part of the length the width was about 2 mm. These crystals frequently began growth by the addition of longer and longer crystals to the side of the last crystal laid down. This accounts for the triangular point frequently seen on these large crystals. Sometimes these flat crystals were nearly square and again diamond shaped. Frequently the flat would develop in places as a rolling surface and also be distorted at the edges. But in any given run with fixed resistance coils in series with the oven heater, there was an unmistakable resemblance between all the crystals formed in a given vicinity of the tube. The largest crystals of this form appeared in a tube in which the air pressure had been reduced to less than 0.01 mm. previous to the sealing off of the tube.

The crystal groups to the left in Fig. 3 are also typical of those that were formed in one tube. They were as long as 4 mm. and as wide as 0.8 mm. They were the result of uniform twinning in such a manner that an open or closed V-shaped gauge was formed by each spine.

Yet another interesting formation that appeared once was a large number of very flexible sheets, sometimes 4 mm. long and as wide as .6 mm. They developed largely one in a place. As they waved about freely by slight air currents, they much resembled a miniature aluminium leaf as used in an electroscope. The thickness of one of these was of the order of 0.01 mm. The other forms described above showed no such flexibility at all. The relative dimensions of two of these crystals may be estimated from the reproduced photograph in Fig. 5. The length of the longest is about 3 mm.

The crystals that formed at the edge of the metallic sheath were only occasionally like those described by Muthman. Fig. 3 shows a photograph of a much larger formation, some as large as 4 mm. which appeared



Fig. 1.

Magnified hexagonal crystals, natural size of single crystals not over 0.1 mm. in width.



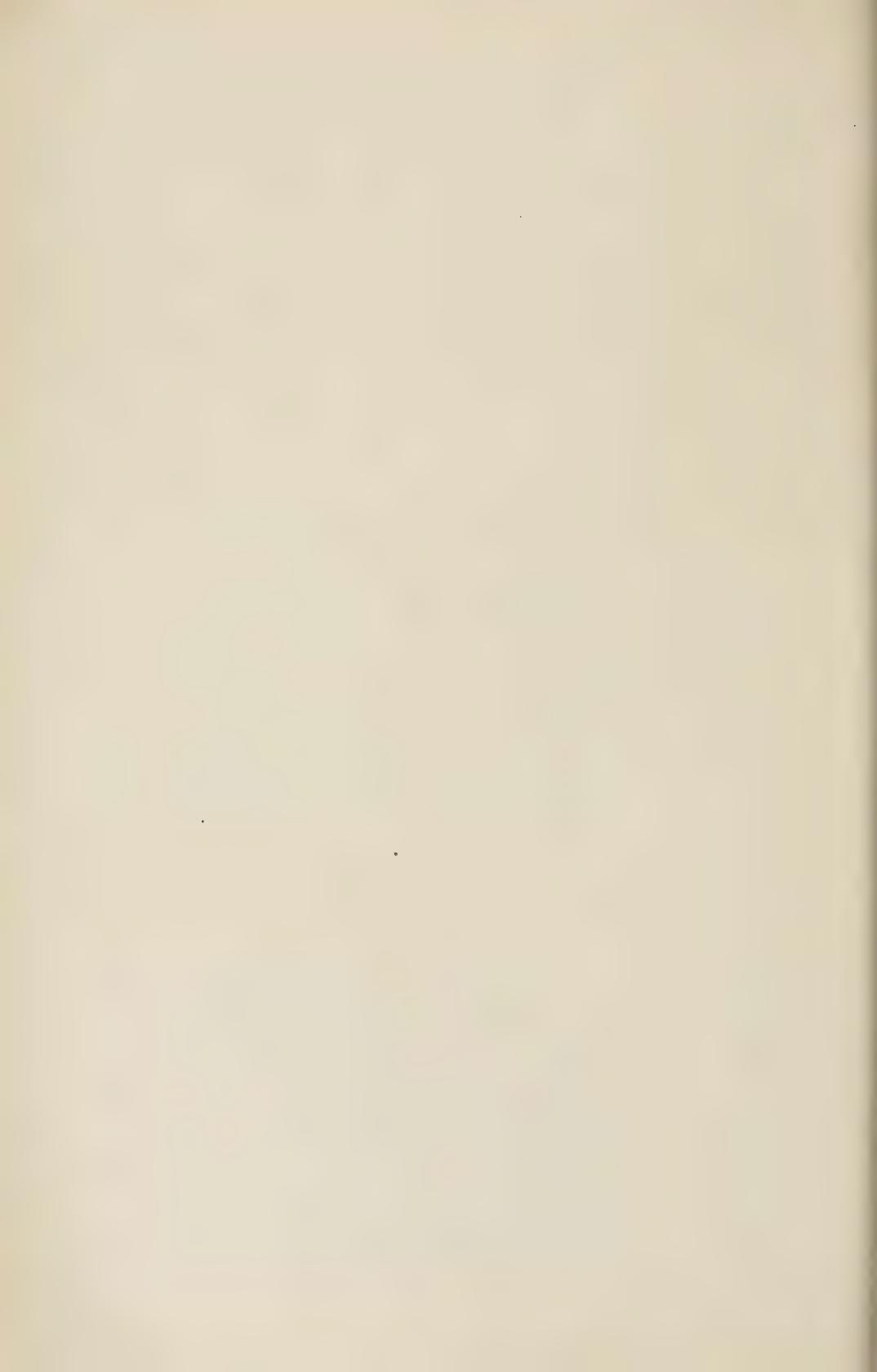
Fig. 2.

(a) Groups of acicular crystals to the left. Natural size of longest ones about 11 mm.
(b) Growth of lamellar crystals in lower right-hand corner, the largest of which as seen in the figure was about $9.0 \times 2 \times 0.4$ mm.



Fig. 3.

The lower part of the photograph shows the growth of single and twinned crystals of



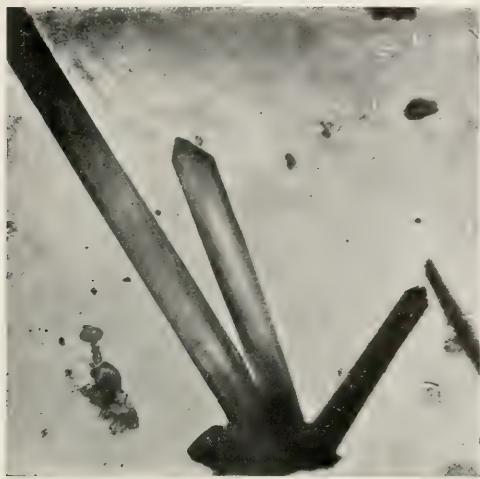


Fig. 4.

The above crystals are the same form as those shown in Fig. 3, but were photographed by transmitted light with a magnification of about 100 times.



Fig. 6.

Lamellar crystals of gradually increasing width. Magnification about 100. Note the striations making an angle of about 35° with the edge.



Fig. 5.

Two crystals of flexible lamellar type. The longest of the above was about 4 mm. long. The width and thickness may be estimated from the reproduction.



Fig. 9.

Crystals of metallic selenium by sublimation. Acicular hexagonal and acicular with side branches. Side branches perpendicular to stem are hexagonal. Those leaving at angle of 60° are lamellar plates showing parallel extinction.

under similar circumstances. Some of the same crystals were magnified much more and photographed by transmitted light as seen in Fig. 4.

The manner in which some of the semi-flexible lamellæ developed is shown by the photograph (transmitted light) in Fig. 6. The striations can be seen running across the surface at about an angle of 35° . With the aid of polarized light these striations become much more marked. They indicate the way in which the large sheet lamella are sometimes built up.

Yet other crystal forms of small dimensions that appeared under the microscope are shown in Fig. 7. The largest of these was about .05 mm. All of these were observed many times. However they were too small for a study of their electrical properties.

Unfortunately all the large crystal forms that I have described were formed at high temperatures. When we have obtained a satisfactory temperature regulator, we shall endeavor to obtain large-sized crystals at about 150° . No doubt more constant and better defined temperatures will produce more regular and larger crystals of the types that I have described, and perhaps new ones.

It is probable that all the crystals belong to the third crystal system, but before this can be decided definitely I believe that it will be at least advisable to obtain more large crystal forms, in order to determine accurately the angles between the faces.

Naturally the question arises as to why selenium crystallizes in so many forms at so nearly the same temperatures. I wish to proclaim a most profound ignorance as to this question. However there is strong indication that the partial pressure of the vapor of selenium and the temperature gradient in the tube at the place of formation are the prime factors. For example I have noted repeatedly that the thin lamellar form appeared when the oven temperature was low, where the amorphous selenium was placed for sublimation. Without doubt the conditions for formation of the crystals should be studied more carefully.

A photograph of some interesting crystals formed at atmospheric pressure is shown in Fig. 9.

THE PROPERTY OF DOUBLE REFRACTION.

All the forms of metallic selenium that have thus far been observed display a distinctly metallic appearance by reflected light. The surfaces

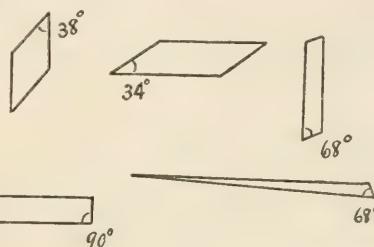


Fig. 7.

were nearly always quite plane and consequently, as the photographs show, the crystals appeared very light or very dark depending on the position of the surface angle with regard to the direction of maximum illumination. It is to be observed in Figs. 2 and 3 that the diffuse light is much less than that from the white paper which served as a background. Even the fine-grained crystal masses formed at lower temperatures and shown in Fig. 3 show a distinct black with contrasting white specks here and there. Likewise all the crystal forms except the acicular ones transmit light even through great thicknesses, and it is interesting to note that wherever the crystal transmits light it displays the property of double refraction. When examined under crossed nicols the transmitted light is most frequently some tinge of deep red, but various formations and thicknesses of crystal show the transmitted light to be distinctly a blue, yellow, orange, green or even white. The fully developed rhombohedral hexagonal crystals in Fig. 1 show a deep ox-blood red under crossed nicols. The transmitted light seems to appear as a body color in the crystal. This may be due to a deviation or scattering of the light inside the crystal. In a lamellar crystal such as shown in Fig. 6, several variations of color are observable at different places. The striations become particularly distinct under crossed nicols by the variation of color and color density.

The elementary crystal forms and the position in which they show extinction of light under crossed nicols are shown approximately correct in Fig. 8. The Nicol prisms are placed as shown by the arrows. The dark positions are those of light extinction and the light positions those in which the light was readily transmitted, in some color or other. The crystal *a* is for one having acute angles of about 35° . Crystal *c* is obviously the multiplication of *a*. Crystal *b* is one having 68° angles.

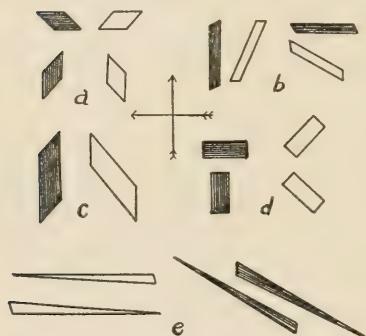


Fig. 8.

Its axis obviously runs lengthwise of the crystals. In *d* is a distinctly right-angled lamellar form, also with optic axis running lengthwise of the crystal. The crystal *e* which is also representative of a large number that were observed, showed the optic axis to run parallel to the very short edge. The acute angle here was about 68° . Thus this crystal may be regarded as built up of a large number of *b* crystals of gradually increasing length. It happens that all the crystals represented in Fig. 8 were

drawn under the same magnification, but they might have been chosen in widely varying sizes. It appears contrary to first expectation that the crystal in Fig. 6 for example is not built up of units of *e*, but rather of units of the crystal *b*. Under crossed nicols it shows extinction parallel to the striations. The crystal in Fig. 5 when viewed flatwise shows extinction parallel to the length of the crystal, indicating the optic axis to be lengthwise of the crystal. This long and flexible crystal may therefore be regarded as built up of the crystals of type *d*, in Fig. 8. The crystals in Fig. 1 show extinction parallel to the long crystallographic axis.

It may be of passing interest to deviate from the topic of this paper to note that the glittering red plates of the red crystalline variety of selenium show double refraction and also that they are not at all metallic in appearance, nor do they show electrical conductance even under very high pressures.

Some time ago the depth of penetration of light into selenium¹ was deduced to be greater than 0.014 mm. This result is very much larger than that of other observers. Pfund,² for example, found the depth to be about 10^{-6} cm. White³ on the other hand believed his selenium blocks indicated a greater penetration than any result indicated above. It seems that the depth of penetration should and does vary with the size, character and positions of the crystals. I have observed a large amount of light transmitted through a lamellar crystal such as shown in Fig. 2 of thickness as great as 0.3 mm. This transmitted light was a deep red and was deviated from its path on emergence through a large angle, perhaps 40° . Thus in a mixture of small crystals adjacent to each other the path might be devious indeed. There is no reason to believe that the light or the light action might not travel several millimeters in a well-formed crystal. Evidence will be mentioned later which indicates that the total number of electrons liberated does not vary greatly whatever may be the deviations of the light.

THE EFFECT OF PRESSURE.

The pressure effect on selenium was discovered in 1905⁴ showing a very large increase of conductivity for increased pressure up to 1,000 atmospheres. Montèn⁵ extended the study independently up to 3,000 atmospheres and observed conductivity changes more than a hundred-

¹ PHYS. REV., 34, p. 201, 1912.

² PHYS. REV., 28, p. 324, 1909.

³ Loc. cit.

⁴ PHYS. REV., Vol. 20, p. 185, 1905.

⁵ Arkiv för Matematik, Astronomi och Fysik, Bd. 4, No. 31, p. 1, 1908.

fold. About the same time a study of the light sensitiveness under varying hydraulic pressures¹ very decidedly indicated that the pressure produced a genuine change in the selenium and did not alter the contact resistances. This argument was based on the presumption that no part of the light action was of a nature of alteration of contact resistances. A recent consideration of the similarity of certain physical properties in light-sensitive selenium and crystal contacts² has led the author to intimate that the early presumption referred to above might be wrong. White's recent work³ with selenium blocks showed the largest change of resistance by light to take place at the electrodes.

A study of a single crystal, in contact with plane electrodes, under varying pressure should reveal important information as to the seat of the pressure effect in ordinary light sensitive selenium as well as in the individual crystal. This pressure effect was easily studied by placing the crystal between two surfaces as shown in Fig. 10. The pressure was increased by merely adding weights. This pressure was applied in the

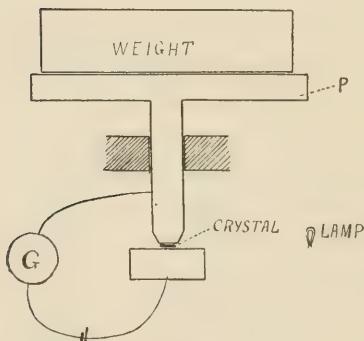


Fig. 10.

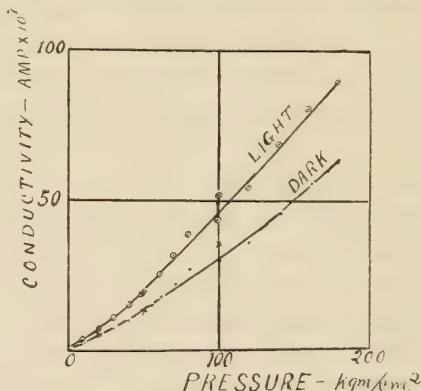


Fig. 11.

direction of the flow of current. The curves in Fig. 11 show the remarkable variation of the conductivity of a single lamellar crystal such as shown in Fig. 2 with change in pressure. The lower curve is the conductivity in the dark and the upper one is for the conductivity in the light. In the dark the conductivity increases about 120 times for an increase of pressure of 180 atmospheres. The crosses on the curves show the conductivity values both in the light and in the dark as the pressure was released. Thus it appears that the selenium crystal attains a given equilibrium under a given pressure. Under higher pressures the con-

¹ See paper by Brown and Stebbins, PHYS. REV., 26, p. 273, 1908.

² PHYS. REV., N. S., Vol. 1, p. 245, 1912, and Proc. Iowa Acad., 1913.

³ Loc. cit.

ductivity was unsteady, so that thus far the action of higher pressures is uncertain. However I succeeded in increasing the conductivity of one crystal about a million times by pressure. Under these conditions it was not light sensitive. The fact that there was only a slight hysteresis as illustrated by the fact that the points on the curves shown were not taken in exactly regular order, is strong evidence that the pressure effect is in the selenium crystal and not at the electrode contacts.

THE VARIATION OF THE LIGHT-SENSITIVENESS WITH PRESSURE.

Experimental Results.—With the apparatus shown in Fig. 10 it was easy to determine the light-sensitivity with different pressures. The interesting result followed that the light action increased with increase of pressure. In the following table is given the conductivity (c) in the dark, which prevailed under the varying pressures recorded in the upper curve of Fig. 11, and also the proportional change of conductivity, $\Delta C/C$, produced by constant illumination. The conductivity is indicated in

C	$\Delta C/C$	C	$\Delta C/C$
.5.....	.6	21.6.....	.43
2.0.....	.5	28.5.....	.46
4.5.....	.45	35.....	.50
7.4.....	.42	46.5.....	.46
10.....	.44	55.....	.45
13.....	.42	62.....	.43
17.8.....	.40		

terms of divisions deflection of the galvanometer, G . It is observed that the conductivity in the dark varied by a factor of 124. Within this large range, the light-action as measured by the change of conductivity is directly proportional to the conductivity in the dark. It may be concluded for pressures up to 180 atmospheres, that the percentage increase of conductivity by a given illumination is constant. This result leads to a remarkable interpretation as to the nature of light action.

Interpretation of Result $\Delta C/C = Constant$.—First it will be seen that the resistance exists in the selenium itself and not at electrode contacts. For suppose the light to produce a change of resistance ΔR in the selenium. Then the proportional decrease of resistance by the light, $\Delta R/(Rs + Rc)$, would get constantly greater inversely proportional to the change of resistance, where Rs and Rc are the resistances of the selenium and the contacts respectively. This result would follow whether the light action were at the contacts or in the selenium itself. For pressures of only a few grams the above ratio was sometimes observed to increase with increase of pressure, but with pressures of 50 gm. or more the ratio of $\Delta C/C$ (or $\Delta R/R$) was constant as shown in the preceding table. It is

concluded therefore that contact resistances are of very secondary or negligible consequence in connection with the ordinary light-electric phenomena in selenium crystals. This result is quite consistent with other experiments to be published later.

The constancy of the ratio of $\Delta C/C$ could be explained if it were possible that the increased amount of the conducting component produced by pressure were the only component that could still further be acted upon by light. But this seems so unreasonable, and it is certainly inconsistent with the results obtained by the author in his various works on selenium cells.

The only reasonable interpretation, it seems, must be worked out somewhat along the following line. Suppose a number of isolated conducting centers throughout the crystal and that this number is a function of the pressure. Generally such an insulated center would not conduct at all, but as the pressure becomes greater a large number of these centers would come within each other's confines, thus increasing the conductivity of the crystal. If the number of centers is small, the conductivity should increase as the number of centers. If a given illumination produces a definite number of new centers, then these new centers should bridge over gaps between old centers approximately proportional to the number of gaps filled, which should vary as the number of old centers or circuits. Of course if the selenium should have a very large number of gaps already completed without the light action, then the light would not have the opportunity of completing a circuit so frequently for every center acted upon. In agreement with this notion I found that when pressures, sufficient to increase the conductivity a million fold were applied that the light sensitiveness diminished to practically zero. It may be convenient to modify this explanation later to satisfy the electron theory of conduction. However it may be mentioned that as a result of further experiments with these crystals Dr. Sieg and myself are compelled to revise the electron theory of electrical conduction. These experiments will be described later.

THE ACTION OF LIGHT.

Essentially in the Body of the Crystal.—In view of White's¹ experiments with selenium blocks in which he observed the greatest change of conductivity at the electrode contacts, it seemed advisable to try the same experiment with a single crystal. This time one of the lamellar crystals of about 4 mm. length was chosen. The ends were clamped to silver electrodes as shown in Fig. 12, leaving about 2 mm. between. A movable

¹ Loc. cit.

slit of 0.1 mm. width was placed about 1 cm. in front of the crystal in the path of a parallel beam of light from an arc lamp. The slit was moved along in front of the selenium by a screw attachment. The conductivity was read when the illumination was on the contacts and at various positions between. The result showed the change of conductivity by constant illumination to be almost unvarying throughout the distance between the electrodes and to be slightly less when illuminated at the contacts. This result seems to lead unmistakably to the conclusion that in the crystal studied, light action is essentially a genuine action throughout the selenium crystal. The action was not a surface action, as evidenced by the fact that if the light impinged on the back side of the crystal the effect was unaltered.

The Action of Light Spreads Inside of the Crystal.—With the arrangement shown in Fig. 12 the slit was adjusted midway between the two electrodes. Then the slit width was widened .05 mm. on each side at a step, the idea being that if each fraction of the light altered the part of the selenium in its path, that the change of conductivity would be in direct proportion to the width of the beam. This should follow from the fact that the parts of the selenium crystal were resistances in series. However the following is typical of the results obtained.

Slit Width Mm.	Conductivity.	Slit Width Mm.	Conductivity.
0.....	40	.4.....	101
.1.....	72	.5.....	109
.2.....	81	.6.....	118
.3.....	92	.7.....	126

This indicates that the first unit of light that falls on the selenium by diffused light in the selenium crystal or some sympathetic mechanism acts to either side of the path or throughout the crystal. Ever after that as the path is widened there is only the action of the selenium in the path or its equivalent. The first unit of light produces an excess of conductivity of 22 units, which can only be ascribed to a spreading action inside of the crystal or its equivalent. The above argument presupposes that not all the light absorbed in the selenium can go toward altering the conductivity, or further that the absolute alteration of the value of conductivity decreases with increased illumination.

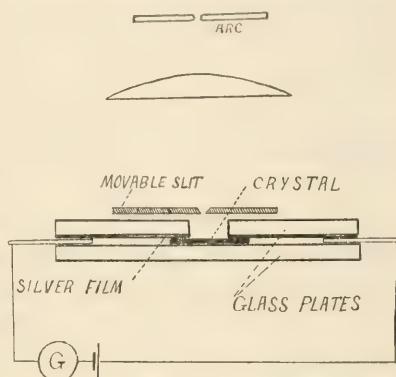


Fig. 12.

The Variation of the Conductivity Change with the Light Intensity.—In the previous part of the paper, it was noted that the change in conductivity by a given illumination was proportional to the conductivity in the dark. This may be written in the form $dC/dI = k \cdot C$, providing that for very small illumination intensities the constant k should remain unchanged. By the integration of the above equation is obtained the value of the conductivity for any intensity, as $C = C_0 e^{kI}$, where C_0 is the conductivity in the dark.

I have not yet had the time to check this equation with more direct experiment.

ACTION OF TEMPERATURE.

Dieterich¹ has recently shown that the character of the wave-length sensibility curves can to a large degree be controlled by the heat treatment of the selenium during annealing, particularly by the temperature at which the selenium was heated. For example, he found that the annealing at about 200° produced a pronounced maximum in the red end of the spectrum, while if the annealing were about 150° , there was a relatively high maximum about $.55 \mu$. Unfortunately I have not thus far been fortunate in producing large crystals by sublimation at both the above temperatures. Therefore we were not able to investigate individual crystals as to the character of the sensibility curves. However the next best step was taken. A selenium cell form (soapstone frame with parallel platinum wires for electrodes) was placed in a highly evacuated tube in which the selenium was to be sublimated. It was so situated lengthwise of the tube that at the end of higher temperature large crystals of the lamellar type formed in considerable abundance with smaller ones nearby the electrodes. About a centimeter further along the frame where the temperature was perhaps 200° was deposited an even finer crystalline structure of unknown texture. After remaining in the tube several days, almost the entire framework revealed in the presence of intense illumination a large number of glittering crystal faces, resembling in a striking manner the appearance of freshly fallen snow in bright sunlight. Except for the crystal faces in the selenium that were at just the right angle to the observer the background was relatively dark.

By the apparatus recently described by Brown and Sieg² we obtained the sensibility curve for the crystal masses at two places in this selenium bridge. For the crystal mass supposedly sublimated at the higher temperature, the upper curve in Fig. 13 was obtained, while for the selenium deposited at the lower temperature the lower curve in the figure was

¹ PHYS. REV., N.S., June, 1914.

² PHYS. REV., N.S., 2, p. 487.

obtained. Thus, contrary to Mr. Dieterich's result referred to, the red maximum appears in the crystals formed from the higher temperature. However it must be noted that this maximum is not in the same position as the maximum which Mr. Dieterich obtained at lower temperature. The cause of the shifting of the maximum will be searched for by the investigation of separate crystals.

GENERAL CONSIDERATIONS.

The present status of the theory of light sensitive selenium points towards a separation of the complex elements along three lines, the light sensitiveness inherent in a given crystal structure, the varying action because of varying refraction, scattering and penetration, and the minor alterations due to the indirect action of the light on the contacts. In view of White's work it seems that contact resistances play a greater part in selenium blocks than in selenium crystals. Whether varying pressure will alter the character of the curves, will depend perhaps on the likeness or unlikeness of the light action for different parts of the spectrum. This point is under investigation at the present time. Also an attempt is being made to locate what characteristics of sensibility curves are seated essentially in individual crystal forms.

This much at least is settled: that the entire action of light in certain crystals at least is in the body of the selenium and not located either at the electrodes or at the surface layer.

Perhaps in the so-called selenium cells the varying temperature action as well as the varying pressure and light action are involved in connection with contact resistances. By placing high pressures, a few atmospheres, on a single crystal of selenium we should be able to eliminate this contact resistance and thereby arrive at the true temperature coefficient of a pure form of selenium and also the true light sensitiveness at various temperatures.

The action of light seems to be in centers inside the crystals and does not necessarily involve the existence of more than one complete crystalline

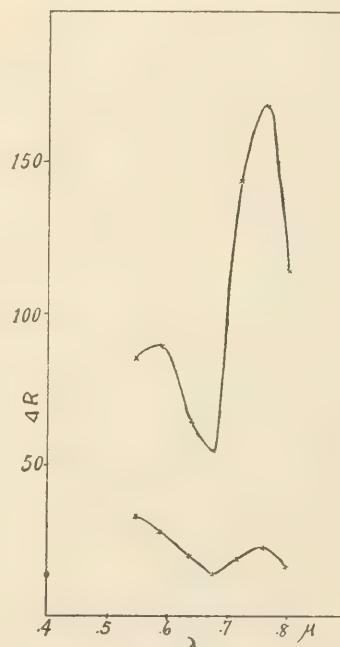


Fig. 13.

form. These centers inside the crystal resemble the so-called active centers in zinc sulphide as described by Rutherford.¹

The specific conductivity of the crystals tested varied between 200 ohms and 10^7 ohms depending on the pressure applied. Judging from the conductivity, it would seem that the selenium in White's selenium blocks existed under an internal strain as a result of crystallization in a rigid form. If so we should expect different stress inside the blocks from what it was near the surface. Possibly some such basis might account for the increased photoelectric properties at the electrode contacts.

SUMMARY.

1. A large number of new crystals of metallic selenium have been formed, some of which are of very large size.
2. All of these forms except one are very transparent selectively to light, a large amount of light penetrating to a greater depth than 0.2 mm.
3. All the forms tested are conducting, showing a specific conductivity varying between 200 and 10^7 .
4. All the crystal forms but one have been observed to be doubly refracting.
5. All the crystal forms increase in conductivity when illuminated.
6. The action of light is in the selenium itself and not at the contacts.
7. Mechanical pressure produces a genuine change in the selenium which may alter the conductivity more than a thousand times.
8. The absolute change of conductivity in one crystal by constant illumination was proportional to the conductivity in the dark, when that conductivity was altered by pressures between 1 and 180 atmospheres.
9. The temperature at which the crystals sublime in mass has been shown to influence the character of the wave-length sensibility curves.
10. It has been shown that the production of individual crystals of metallic selenium of large size opens up a large field of investigation, which promises to be free from some of the possible complexities in selenium cells.

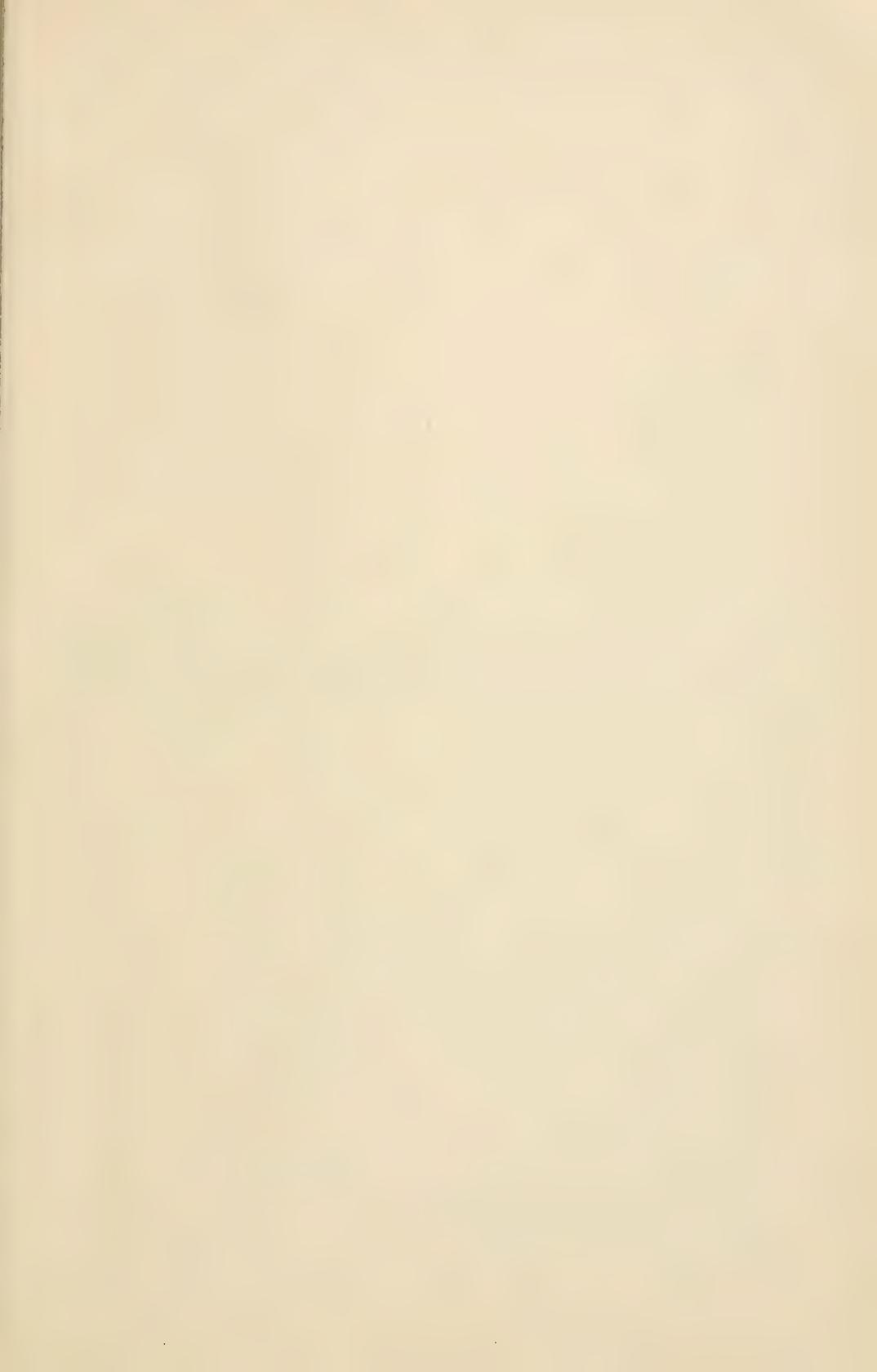
In conclusion I desire to thank Mr. M. H. Teeuwen for his assistance in designing and constructing apparatus, Mr. Scott Walker for assistance in taking observations, and Professor G. F. Kay, of the Geology Department, for the use of apparatus and also for his kind and generous help in the crystal studies.

THE PHYSICAL LABORATORY,

THE UNIVERSITY OF IOWA,

April 11, 1914.

¹ Proc. Roy. Soc., A, 83, p. 561, 1910.



PHASE RELATIONS IN THE ACOUSTIC SHADOW OF A
RIGID SPHERE; PHASE DIFFERENCE AT THE EARS

PHASE RELATIONS IN THE ACOUSTIC SHADOW OF A RIGID SPHERE; PHASE DIFFERENCE AT THE EARS.

BY G. W. STEWART.

SATISFACTORY explanations of the many phenomena in sound localization can be realized only after the bases are laid for a successful discrimination between physical and psychological factors. The experiment in localization which seems to be the most difficult of explanation is that first noted by Rostosky,¹ independently reported by Rayleigh² and afterward studied by Rayleigh,³ More and Fry,⁴ Myers and Wilson⁵ and More.⁶ These experiments show that there is an illusion of localization if there are produced at the ears various differences in phase obtained from the same source or from sources of the same frequency. If the difference in phase is 0° , the sound appears directly in front. If the difference is 90° , and the phase of the right ear is leading, the sound appears to be on the right side. When the difference becomes 180° , the sound appears in front or in the rear, and when the difference is 270° the sound is at the left. Finally, at 0° phase difference the sound appears in front. These points are not the only ones, for, as a matter of fact, the sound seems to pass continually about the head, internally or externally, from one of the points to the other. These results are only a portion of those obtained with varying phase differences, but they are sufficient to show that an understanding of the varying phase differences produced at the ears by a rotation of the head, the source of sound being at a given distance, is needed, for it would be a distinct assistance in a discussion of the influence of a difference in phase at the ears. .

A brief extension of a theory already published⁷ will give the desired information. Let the source be confined to a small area on the face of a rigid sphere, and let the velocity of this source region be harmonic with the same magnitude throughout.

¹ *Philosophische Studien*, 19, 1902, p. 557.

² *Phil. Mag.*, 13, 1907, p. 214.

³ *Phil. Mag.*, 13, 1907, p. 316, and *Proc. Roy. Soc., London, A* 83, 1909, p. 61.

⁴ *Phil. Mag.*, 13, 1907, p. 452.

⁵ *Proc. Roy. Soc.*, 80, 1908, p. 260, and *Brit. Jl. of Psych.*, 11, 1908, p. 363.

⁶ *Phil. Mag.*, 18, 1909, p. 308.

⁷ G. W. Stewart, *Phys. Rev.*, XXXIII, No. 6, 1911, p. 467.

ψ represents the velocity potential.

a represents the velocity of sound.

r represents the distance from center of sphere.

c represents the radius of the sphere.

dS represents an element of surface.

$$k = \frac{2\pi}{\text{wave length}},$$

$$\gamma = k(at - r + c),$$

$$F = \Sigma \frac{2n+1}{2} P_n(\mu) \frac{\alpha\alpha' + \beta\beta'}{\alpha^2 + \beta^2},$$

$$G = \Sigma \frac{2n+1}{2} P_n(\mu) \frac{\alpha\beta' - \alpha'\beta}{\alpha^2 + \beta^2}.$$

α, α', β and β' are defined in the article cited. Then

$$\psi = \frac{ka}{2\pi r} (F \sin \gamma + G \cos \gamma) \iint U dS. \quad (1)$$

The condensation s is related to ψ by the following

$$s = -\frac{\dot{\psi}}{a^2}, \quad (2)$$

where s is related to the densities by the equation $\rho = \rho_0(1 + s)$.

Substituting (1) in (2) we have

$$s = -\left[\frac{k}{2\pi r a} \iint U dS \right] \sqrt{F^2 + G^2} \cos(\gamma - \epsilon), \quad (3)$$

if $\epsilon = \tan^{-1} F/G$.

$\iint U dS$ is the surface integral over the source region of the maximum value of the velocity U , and is therefore independent of r, t , and μ , or the cosine of the angle between lines joining the center of the sphere with the source of sound and the selected point. F and G vary with r and μ . Given a value r , *i. e.*, points on a concentric sphere, the maximum values of s will change with values of $\sqrt{F^2 + G^2}$, and at any given time the phase of s will vary from point to point on this sphere with values of ϵ, γ varying only with the time. Differences of phase can therefore be readily found by obtaining the different values of ϵ .

When these phase differences are ascertained, it is not difficult to obtain the phase differences on the sphere with the source at a distance r . For according to the Helmholtz reciprocal theorem,¹ if the source is at A , the resulting velocity potential at a second point B is the same both in *magnitude* and *phase* as it would have been at A , had the source

¹ Rayleigh, Theory of Sound, Vol. II., p. 145.

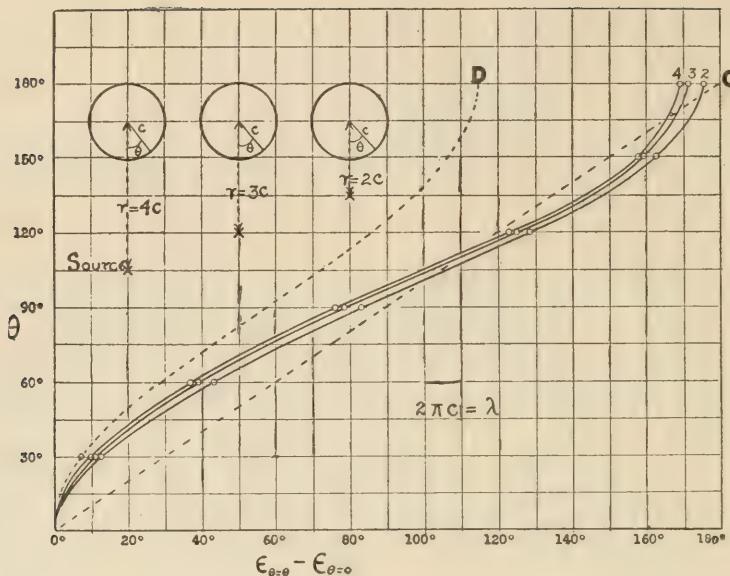


Fig. 1.

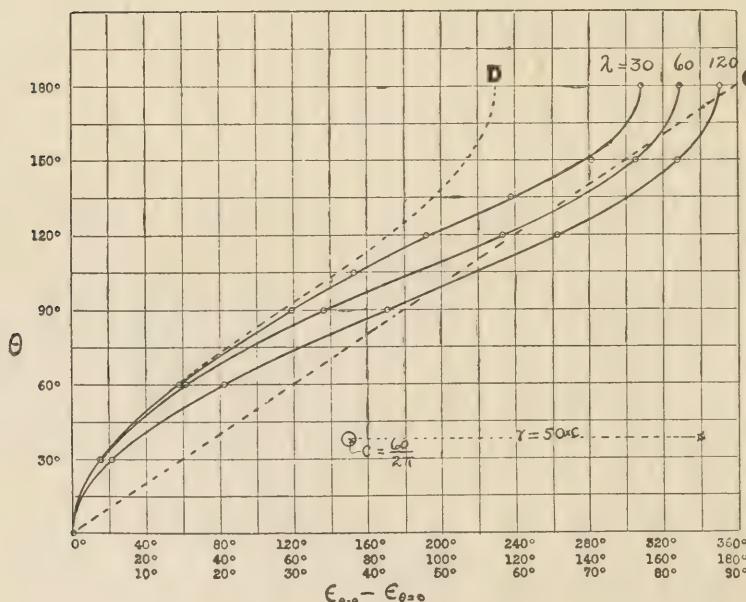


Fig. 2.

of sound been at B . According to (2), the same reciprocal relation holds for the condensation s . Hence (3) will be used for the case where the source is at a distance r and the phase relations are desired on the rigid sphere itself.

RESULTS.

We desire to know the variations of phase for positions on the sphere from 0° to 180° where these are taken on any great circle with 0° at the point nearest to the source which is at a distance r from the center of the sphere. The necessary computations for values of F and G are very laborious and consequently the conditions chosen were determined by

TABLE I.

Wave-length = $2\pi c$.

θ	Distance $r=2c$.		$r=3c$.		$r=4c$.	
	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$
0°	+1.4646	0.0°	+1.0573	0.0°	+0.9232	0.0°
	+0.2571		+0.2566		+0.2506	
30°	+1.1123		+0.9349		+0.8556	
	-0.0496	12.51°	+0.0451	10.88°	+0.0778	9.99°
60°	+0.5389		+0.5909		+0.6018	
	-0.3531	43.19°	-0.2796	38.97°	-0.2376	36.72°
90°	+0.1111		+0.1816		+0.2184	
	-0.3648	83.03°	-0.3878	78.45°	-0.3912	76.00°
120°	-0.1315		-0.1193		-0.1086	
	-0.2401	128.64°	-0.3040	125.07°	-0.3374	123.02°
150°	-0.2399		-0.2708		-0.2880	
	-0.1244	162.54°	-0.1823	159.69°	-0.2190	157.83°
180°	-0.2629		-0.3131		-0.3402	
	-0.0717	174.70°	-0.1300	171.10°	-0.1652	169.28°

values that had already been obtained in other work. These are, however, sufficient to indicate what is to be anticipated in the case of various frequencies and distances from the sphere. The accompanying tables, I. and II., give the numerical values. The accompanying curves, Figs. 1 and 2, present the results with sufficient clearness, but the tables are necessary in order to make a more traceable record. In Table I. and Fig. 1 the distance is varied. The results are obviously applicable for any value of c , the wave-length always being equal to the circum-

ference of the sphere. In the case of the head, the circumference may be taken as 60 cm. In Table II. and Fig. 2 the numerical value for c is chosen with special reference to the head as the sphere, but the results would hold for any sphere if the relative values of wave-length, circumference and distance are retained.

TABLE II.

 $r = 477$ cm. $c = 60/2\pi$

θ	Wave-Length, 120 cm.		60 cm.		30 cm.	
	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$	F and G .	$\epsilon_{\theta=0} - \epsilon_{\theta=0}$
0°	+0.5371 +0.1499	0.0°	+0.6830 +0.2320	0.0°	+0.7737 +0.2016	0.0°
30°	+0.5346 +0.0966	5.34°	+0.6800 +0.1308	7.87°	+0.7803 -0.0062	15.06°
60°	+0.5077 -0.0447	20.60°	+0.5899 -0.1215	30.42°	+0.5097 -0.4826	58.04°
990°	+0.4280 -0.2201	42.81°	+0.3149 -0.3665	68.10°	-0.1478 -0.5609	119.37°
105°					-0.3638 -0.3314	152.27°
120°	+0.3060 -0.3650	65.62°	-0.0599 -0.4307	116.68°	-0.3879 -0.0194	191.75°
135°					-0.2378 +0.1359	237.19°
150°	+0.1955 -0.4467	81.96°	-0.3367 -0.3522	152.37°	-0.0235 +0.4026	281.27°
180°	+0.1517 -0.4708	87.73°	-0.4297 -0.2959	164.21°	+0.2131 +0.4892	308.14°

In both figures $\epsilon_{\theta=0} - \epsilon_{\theta=0}$ represents the phase difference between the point $(c, \theta = 0)$ and all points $(c, \theta = \theta)$, the straight line C gives the differences of phase that would occur if the condensation travelled around the circumference with the velocity of sound, and the curve D indicates the variation in phase that would occur along the diameter if the sphere were absent. The same accuracy does not hold for all the results. Those for a wave-length of 120 cm. in Fig. 2 and those of Curves 2 and 3 in Fig. 1 are very accurate, but the computations for the three other curves have not been so carefully checked. Values for 105°

and 135° were introduced to assist in locating the correct curve with the wave-length 30 cm.

Attention might be called to several points of interest.

1. The effect of increasing distance is small.
2. The phase changes the most rapidly in the neighborhood of the portion designated by 90° – 120° in Fig. 1.

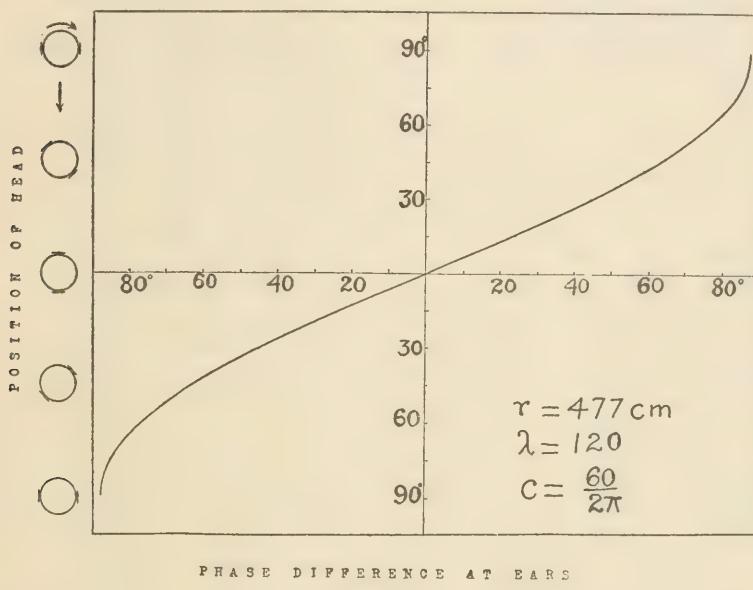


Fig. 3.

3. In most of the curves shown, in a portion of the region designated by $120^\circ < \theta < 180^\circ$ in Fig. 1, the phase differs from that at 0° by an amount in excess of what would occur if the sound travelled directly up to the point $\theta = 0^\circ$ and then followed the surface of the sphere with the velocity of sound. This is a surprising result, if one does not give thought to the fact that the condensation is a resultant.

4. The interesting result just stated does not exist with the wave length 30 cm. That this should be the case appears reasonable when one considers that the effective wave front is not so large with the smaller wave-lengths.

5. The difference of phase is relatively less with the decreasing wave length.

DIFFERENCE IN PHASE AT THE EARS.

The difference in phase at the ears can readily be obtained from the preceding results if one supposes the head to be a rigid sphere with the

ears diametrically opposite. The results for the case of wave length 120 cm., sphere circumference 60 cm. and distance of sound 477 cm. from the center of the sphere, are given in accompanying Fig. 3. The phase difference changes the most rapidly when the source of sound is in front or behind the hearer. These results give an estimate of the physical aspect of phase differences at the ears.

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The Seat of Light Action in Certain Crystals of Metallic Selenium, and some New Properties in Matter. By F. C. BROWN, *Ph.D.*, and L. P. SIEG, *Ph.D.*, Assistant Professors of Physics, State University of Iowa, U.S.A.

FROM time to time new experiments are performed which leave doubt as to the seat of light-action in selenium. The most recent experiments were performed with selenium blocks by White*. The selenium blocks showed a greater change in conductance when illuminated at the electrode contacts than when illuminated on other parts of the surface. We have recently succeeded in producing several forms of large crystals of metallic selenium † which have enabled us to determine several interesting facts concerning the seat of light-action in selenium. The advantages of a single crystal for studies of this kind are perhaps obvious. The contact resistances are limited to the electrodes, and knowing this fact, the magnitude of such resistances can be determined. Also it makes it possible to locate the seat of light-action as well as something concerning the nature of light-action.

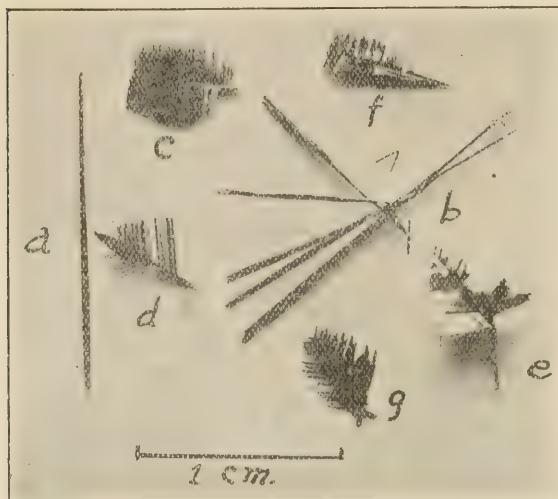
The Conductivity is Distributed throughout the Crystal.—In order to locate the seat of change of conductivity in a crystal it was first necessary to determine where the conductivity existed. For this an acicular crystal of about 8 mm. length was used. A cluster of such crystals is shown in fig. 1. The width and thickness of the crystals were each about 0.2 mm. These needles, when fully developed, had six surfaces, with angles of about 60° between adjacent surfaces. The leaf-like forms (c) and (d) typify interesting formations of acicular crystals. First the central spine of a hexagonal crystal like (a) was formed. Then by certain changes in the oven conditions the side branches grew out from the central spine as shown. Those in (c) were regularly developed hexagonal needles, which transmitted little or no light. But the branches in (d) were thin plates, with acute angles of about 65° . As described in a previous paper (*loc. cit.*) these crystals transmitted a deep red light when placed between crossed nicols. Likewise they showed extinction parallel to the long axis of the crystal. In some

* G. W. White, *Phil. Mag.* [6] xxvii. p. 370 (1914).

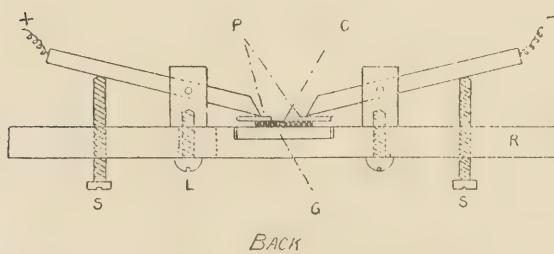
† F. C. Brown, *Phys. Rev.* n. s. 1914.

forms like (c) and (d) the branches grew entirely together as the crystals developed, so as to form an apparently plane surface. They sometimes formed a solid lamellar crystal form, and were then excellent reflectors of large dimensions.

Fig. 1.



The form (e) is made up of four rows of branches placed 90° apart. A large number of other crystal forms have been described (*loc. cit.*), all of which are light-sensitive. However, the forms described in this paper were best adapted to the argument.

Fig. 2.
FRONT

This crystal was laid on a glass plate, G, and silver electrodes, P, P, were pressed against the upper surface of the

crystal by screws, S, as shown in fig. 2. The whole was mounted on a hard rubber plate, R. With the crystal placed in this manner there was not much change in the conductance on altering the pressure at the contacts. In view of the very large change in conductance which was observed when the entire region between the electrodes was placed under a few atmospheres pressure, and in view of the well-known change of conductivity with pressure in ordinary crystal contacts, it is concluded that only a relatively small resistance exists at the electrode contacts. The following observation adds further evidence towards this conclusion. With the contacts 2·5 mm. apart on one crystal the resistance was about 10^7 ohms, and when the distance was shortened to about 0·5 mm. the resistance diminished by a factor of 4·8. Obviously this requires that the resistance shall be distributed somewhat uniformly along the crystal.

The Change of Conductivity acts throughout the Crystal.—In order to show that not only the conductivity, but also the change of conductivity, is not limited to the surface or to the contacts, the selenium was illuminated alternately from the front and from the back. The distance between electrodes was about 3 mm. The key to this experiment lay in the fact that the path along the front side of the crystal was shorter than that along the back side. The current in going by the back side had to traverse the thickness of the crystal twice. Thus we may regard the front and back sides of the crystal as parallel conductors, where the highest resistance is found in the back side. Then suppose for the time being that the light-action produces an effect near the surface only, and that this action is constant. Imagine the selenium illuminated with a narrow beam of light which acts on a portion only of one of the parallel conductors. Obviously, with these assumptions, the given illumination should produce a greater total change in the conductance when it falls on the front side of the crystal than when it falls on the back side. This idea was carried out by focussing an illuminated slit on the crystal. This focussed image was 0·2 mm. wide. The image was moved along the crystal 0·5 mm. at a step, and the corresponding conductance was noted. Then the selenium was reversed so as to expose the back side to the illumination, and a similar set of observations was made. A number of such sets were taken, a sample of one of which is given in the accompanying table.

TABLE I.

Acicular crystal, $8 \times 0.2 \times 0.2$ mm.		
Nature of illumination.	Conductance with front side illuminated.	Conductance with back side illuminated.
In dark.	27, 26.5	26.5
On contact No. 1.	38, 38, 39	38, 39
0.5 mm. from contact.	65, 67, 64	64, 64
1.0 " " "	69, 69, 69	53, 52
1.5 " " "	63, 64, 61	42, 44
2.0 " " "	55, 54, 53	38, 40
2.5 " " "	47, 48, 55	40, 42
3.0 " " "	45, 46, 44	39, 43
On contact No. 2.	33, 33, 31	33, 37

Lamellar crystal, $3 \times 1 \times 0.2$ mm.		
In dark.	61	61
On contact No. 1.	68, 70	71, 71, 81, 84
0.25 mm. from contact.	94, 94	93, 94
0.50 " " "	96, 99	102, 103
0.75 " " "	98, 100	99, 100
1.00 " " "	98, 95	94, 95
1.25 " " "	90, 88	86, 86
1.50 " " "	85, 86	82, 82
1.75 " " "	86, 87	86, 82
2.00 " " "	80, 76	86, 85
On contact No. 2.	64, 64	76, 78

The above data, which are typical of a large number of observations, call forth the following conclusions:—

1. The change of resistance by light is a property of the crystal, and not an action taking place at the contacts.
2. Illumination at different points along the crystal produces approximately the same effect at all places.
3. The crystal is changed in conductance by approximately the same amount, whether the illumination is on the side of the contacts or on the opposite side.

From these three we draw the general conclusion that the light acts throughout the crystal, and that the conductivity is almost uniform throughout the crystal.

Incidentally it should be noted that all faces of these metallic selenium crystals seem to be excellent reflectors of light, perhaps less than 5 per cent. entering the crystal, but no exact measurements of this point have yet been made. On the other hand, we have measured the absorption of light

from the selenium surface in the so-called selenium cell*, and found more than 98 per cent. to be absorbed in all parts of the spectrum.

In comparing the observations just referred to it must be remembered that in the front side illumination no light reached directly either the crystal or the point of contact when the beam was on the electrode. On the contrary, when illuminated from the back the light fell on the crystal itself in the experiment marked "On contact" in the table No. 1. A glance at fig. 2 will make this point clear. Further, it is interesting to note that as long as any light fell on any part of the crystal there was a marked change in the conductance, even though the illuminated portion of the crystal was not in direct line of conductance. This remarkable property of transference of action will be further verified and discussed later in this paper.

It may be mentioned that the points of contact between the crystal and the electrodes were illuminated in a separate experiment, in which the electrodes were semi-transparent silver films deposited on glass, and the action at the electrode contacts was found to be slightly less than elsewhere.

Another crystal was investigated with the apparatus shown in fig. 2, with a slightly modified procedure. The electrodes were moved so as to be 0·1 mm. apart, and on the same side of the acicular crystal, which was a little over 0·1 mm. thick. Thus the resistance around by the back side of the crystal should be, if the crystal were considered as being nearly isotropic in its conductivity, approximately three times that along the front face of the crystal. Supposing the crystal to be uniformly conducting, we should obviously expect a wide difference in the conductance changes between front and back side illumination, providing the light acted only at a small effective depth, or conversely the two light actions should be the same, providing that the light action spread throughout the crystal without apparent absorption. A beam of width 0·1 mm. was let fall first on the front side and then on the back side, after having passed through the same thickness of glass in each case. An average of five readings on the front side showed an increase in the conductance of $29\cdot2 \pm 0\cdot8$, and similarly the back side illumination produced a change of $30\cdot4 \pm 0\cdot5$. These changes are so nearly identical that we are led to believe either that the light penetrates the crystal without absorption, or that the

* Work not yet published.

light on entering the crystal operates a mechanism which controls by secondary action the conductance of the entire crystal.

In the last paragraph we noted two possibilities, viz., either that the light penetrates almost without absorption, or that the crystal is made up of a sympathetic mechanism, which may be operated at various points throughout the crystal. The crystal was of acicular form, and slightly greater than 0.1 mm. in thickness. Not only was it not transparent to a large degree, but under the microscope no trace of light could be seen through the crystal. This was also the case when the crystal was examined between crossed nicols. Thus the second conclusion seemed unavoidable. But the idea was so novel that it could not be accepted without further confirmation.

Evidence deduced from the Law of Superposition of Intensities.—This confirmation was next sought by illuminating a flat acicular crystal by two twenty-watt tungsten lamps placed in certain combination positions as described below. The point to be established is that illumination from the back side of the crystal acts on the same parts of the crystal, and to the same extent, either directly or indirectly, as those acted on by illumination directed on the front face. For the sake of argument, imagine as before the crystal to be divided lengthwise into two parallel conductors, and further consider that light from one side may, or may not, act on both conductors. The same arrangement of apparatus as that represented in fig. 2 was used, with the addition of the two lamps above noted. Let the two lamps, A and B, be turned on separately and then together, while stationed on the front side, and let the corresponding changes of conductance be noted. From these observations we obtain the law of variation of conductivity change with change of intensity of illumination, or the law of action when one intensity of illumination is added to another intensity at the same places on the crystal. In an ordinary selenium cell this action has long been known to vary, except under very special conditions, with the square root of the intensity of illumination, following the relation

$$\Delta C = K I^{\frac{1}{2}},$$

where ΔC is the change in the conductance in the crystal, K is a constant, and I the intensity. Then if $\Delta_1 C$ and $\Delta_2 C$ represent the changes due to intensities I_1 and I_2 , the change in conductance due to the two acting together should be

$$\Delta C = K [(\Delta_1 C / K)^2 + (\Delta_2 C / K)^2]^{\frac{1}{2}}.$$

Recently one of us* has predicted from theoretical considerations that the above law should hold also for these crystals. Next remove the lamp B to the position B' behind the crystal, so as to illuminate the other side of the crystal with the same effective intensity as it previously illuminated the front face. Now if the lamp at B' acts only on the back half of the crystal and the lamp A acts only on the front half, or even less than half of the crystal, we should have the change of conductivity by A and B together in the positions A and B' equal to the sum of the changes by A and B separately in these same positions. On the other hand, if the effect of the two lamps is the same whether the lamp B is in front or behind, we can conclude without hesitation that the illumination from the front or back produces the same action in the crystal and acts on the same parts. The following table (No. II.) is a sample set of observations which answers the question beyond doubt.

TABLE II.

Both Lamps in front. Conductance with Crystal Illuminated, and in Dark as indicated.

In dark.	By Lamp A.	By Lamp B.	By both A and B together.
66.8	97	98	110.5
68	101	101.5	110.5
67	98	99	110
68	98.5	100	110
—	—	—	—
67.5	98.6	99.6	110.2
$\Delta_1 C = 31.1$		$\Delta_2 C = 32.1$	$\Delta C = 42.7$
$\sqrt{31.1^2 + 32.1^2} = 44.7$			

Same with Lamp A in front, and Lamp B at back.

66	96	96	109
67	96.5	98	109
67	96.5	97	108
67	97.5	97	108
—	—	—	—
66.8	96.4	97	108.5
$\Delta_1 C = 29.9$		$\Delta_2 C = 30.2$	$\Delta C = 41.7$
$\sqrt{29.9^2 + 30.2^2} = 42.4$			

We note that the two lamps A and B acting together produce almost identically the same effect whether they act on the same side or on opposite sides. For the range tested the change in the conductance varies as the square root of the intensity. Thus the conclusion is unavoidable that light

* F. C. Brown, Phys. Rev. *loc. cit.*

action is independent of the side which is illuminated, and further that added intensities produce an effect the same in degree whether impinging on the same or on opposite sides of the crystal. The fact that no light goes through the crystal compels us to believe that the crystal conductivity is controlled by sympathetic centres located throughout the crystal. The nature and distribution of these centres will be discussed in a later paper.

An Apparent Spreading of Light Action.—Since the light can act throughout the depth of the crystal, indirectly it is true but still undiminished by any apparent absorption, why can it not also act to one side of the place struck by the beam of light? This in fact was indicated by the experiment described above, in which illumination beyond the point of contact produced an effect on the conductance. To check this point further two parts of the same crystal were illuminated by two separate beams of light, leaving a small dark space between. The theory is simple. If the action spreads only in the direct path of the beam, and not at all laterally, then the change in the conductance for illumination by two slits should be equal to the sum of the changes when the crystal is illuminated by each of the slits separately. Conversely, if the effects of the two do spread laterally so as fully to overlap, then the change in the conductance should follow the square root law. The following series of observations is typical of several series that were obtained.

TABLE III.
Conductance of Acicular Crystal illuminated, and
in Dark as indicated.

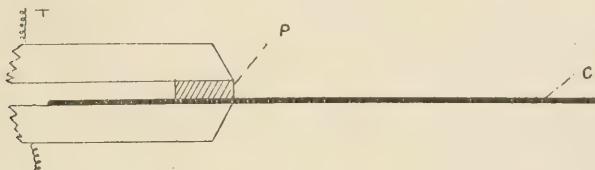
In dark.	By Slit No. 1.	By Slit No. 2.	By Slits Nos. 1 and 2 together.
23	29	28	32
23.2	29	28	31
23	28	27	29.6
22.6	28.2	27.5	29.4
22.6	27.5	27	30.5
22.9	28.3	27.5	30.5
$\Delta_1 C = 5.4$		$\Delta_2 C = 4.6$	$\Delta C = 7.6$
$\sqrt{5.4^2 + 4.6^2} = 7.2$			

From Table III. it is evident that the combined effect is not the sum of the two individual effects. Within the limits of error the square root law holds, and the total combined effect of both slits acting at different places on the same side is identical with that when they act on the same place. In other words, the actions of two separate illuminations overlap

just the same as if they had impinged at the same spot. The mean distance between these two illuminated areas was 3 mm.

The Action of Light in a Crystal is transmitted to a Distance.—The above result led directly to a peculiar experiment with the amazing result that light action may be transmitted laterally to a longer distance than 10 mm. in an acicular hexagonal crystal of metallic selenium without any, at present known, apparent mechanism to carry the action. First a crystal of dimensions $10 \times 12 \times 13$ mm. was placed with one end between silver electrodes, as shown in fig. 3. The conductance in the dark was 110. A beam of light was focussed

Fig. 3.



first near the electrodes, and then moved out to the end step by step, and the following readings of the conductance were observed.

TABLE IV.

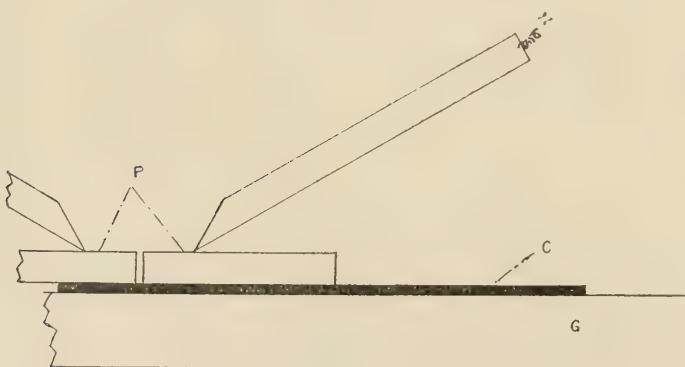
Location of light.	Conductance, C.	Change in Conductance, ΔC .
Off crystal.	110	—
Near electrodes.	144	34
On Step 1.	137	27
“ “ 2.	117	7
“ “ 3.	111	1
“ “ 4.	124	14
“ “ 5.	146	36
“ “ 6.	150	40
On end of crystal.	151	41

This shows, as did also similar experiments with other crystals, that along the crystals there are light-sensitive parts which control the conductivity mechanism of the selenium. For, strange enough, the greatest effect was produced in the crystal above when the illumination was at the end of the crystal farthest from the electrodes, a distance out of some 6 mm. If the current had travelled the entire distance around by way of the illuminated end, it would have gone

about 100 times the distance between the electrodes, and so if the effect of the light had been confined to the neighbourhood of the tip of the crystal, this great change in the conductance could surely not have taken place. We must conclude from this that the conductivity near the electrodes was changed by light acting 6 mm. to one side. In fact there was no discernible diminution in the conductance by removing entirely the projecting 6 mm. of the crystal. This shows quite clearly that the part acted on by light normally contributes nothing directly to the conductance. In another crystal, which was 15 mm. long, we observed a change of conductance by illuminating the end when it was 10 mm. from the electrodes. In this instance the distance from one electrode to the end and back to the other electrode was 170 times the distance between the two electrodes. The sensibility by exposing at the end was almost as great as that prevailing by exposure to light close to the contacts. The cause of the irregularity in the sensibility along the crystal is yet unknown. A number of experiments were made to show that diffuse or scattered light could have made only an inappreciable effect.

One more experiment was performed to make certain that the above action at a distance was not due to a widely varying specific resistance along the different axes of the crystal. The two electrodes were placed on the same side of the

Fig. 4.



crystal about 0.1 mm. apart, and the crystal projected 6 mm. beyond one of the electrodes, as shown in fig. 4. The procedure was to illuminate the crystal at various points to see

of the same result was obtained as related above. The following table represents the results.

TABLE V.

Location of light.	Conductance, C.	Change in Conductance, $\Delta C.$
Off crystal.	115	—
On end.	130	15
1.5 mm. from end.	125	10
3 " "	125	10
4.5 " "	129	14
Between electrodes.	209	94

Just as previously, the action seems to be transmitted entirely along the crystal. However, in this case the effect is relatively less away from the region of conductivity. A further study of this variation may reveal more exact information about the nature of the light action in these crystals. It should be pointed out that the pressure of the electrodes on the crystals and the electrical intensity along the crystals alter their conductance.

It might be asked if this action at a distance might not be ordinary heat action due to the light. This, however, is quite impossible. First, because the action is too rapid. Almost at the very instant the crystal was illuminated the major portion of the conductance change, at a distance away of 10 mm. from the point of illumination, took place. Secondly, by the arrangement shown in fig. 4, the conductance was almost doubled by illuminating the end of the crystal. This was too large to be anything but a light effect, for if the light of the same intensity impinged between the electrodes, the action was never much greater than this.

We have thus far shown certain metallic selenium crystals to possess not only the light-electric properties generally recognized in selenium cells (or bridges), but it is shown that they possess a peculiar sympathetic structure limited apparently only by the crystal surfaces. It may be said that we have a new "Action at a distance." If we can determine the rate of transmission of the action through the crystal, certain information may be obtained as to the nature of the mechanism of transmission. The possible processes that are suggested are, electronic transmission such as exists in the flow of the electric current, transmission by the elastic vibration of the medium, and possibly by the interaction of parts of the atoms moving with velocities approaching that of

light. We have not yet been able to decide if this action can be transmitted from one crystal to another. If it cannot be so transmitted, then it would seem to argue against an electronic transmission such as mentioned above. We propose to test not only the matters of the rapidity of transmission along the crystal, and the possibility of transmission from one crystal to another, but also to determine if a pure heat effect can be transmitted by this same mechanism.

Physical Laboratory,
State University of Iowa,
May 14, 1914.

THE INFLUENCE OF ANNEALING ON THE CHARACTERISTICS OF LIGHT-SENSITIVE SELENIUM.

BY E. O. DIETERICH.

AND extension, by Brown and Sieg,¹ of the work of Pfund in analyzing selenium cells by means of the spectrum revealed the fact that, classified according to their wave-length sensibility curves, a great number of different types of selenium cells were possible. Previous investigations by Pfund,² Stebbins,³ Brown and Sieg,⁴ and Nicholson⁵ pointed to the conclusion that a typical wave-length sensibility curve existed which was essentially the same for all selenium cells, for, in all cases recorded, a maximum in the red end of the spectrum was found. The cells investigated were, in general, made by either Giltay or Ruhmer. The process of making these is a trade secret, but it is quite likely that the same method of crystallization is followed in all the cells of either one of the above types. Pfund, in his earlier experiments, used some cells of his own construction; these, too, were all crystallized in the same manner.

In some later experiments by Brown and Sieg, cells prepared by the author were used. Sensibility curves were obtained which differed widely, some showing a maximum in the red, some having hardly any sensitiveness in the red but a maximum in the blue. An analysis of the data covering the method of construction of these revealed the fact that the crystallization of the selenium took place under different conditions in the different samples. This immediately suggested the possibility that a better knowledge of the conditions governing the construction of light sensitive selenium cells might be of assistance in explaining the action of light sensitive selenium. With this purpose in view, the investigation summarized in this paper was carried out.

This paper will describe the method followed in making the cells, and will show that the resistance and the shape of the wave-length sensibility curves of selenium cells can be controlled by varying the process of annealing. A simple explanation for the different types resulting will also be offered.

¹ PHYS. REV., Series 2, IV, p. 48, 1914.

² PHYS. REV., XXVIII., p. 324, 1909; XXXIV., p. 370, 1912; Phil. Mag., VII., p. 26, 1904.

³ Astrophys. Jour., XXVII, p. 183.

⁴ PHYS. REV., Series 2, II., p. 487, 1913.

⁵ PHYS. REV., Series 2, III., p. 1, 1914.

METHOD OF MAKING.

The cells, of which about 40 were constructed for this investigation, were all of the Bidwell type, *i. e.*, two parallel wires were wound spirally around an insulating form and the spaces between the wires filled with selenium.

The selenium used was some in stick form from Merck. No steps were taken to further purify it, since it is, according to other observers, quite pure. Moreover, Pfund¹ has shown that the presence of metallic selenides does not affect the shape of the wave-length sensibility curve. In a few samples made, rather impure selenium was used, and the cells resulting were not as satisfactory as those made with selenium from Merck. The resistance of these was, in general, very high, and they were sluggish in action although they had essentially the same characteristics as those made from the purer element. Marc² has observed that impure selenium crystallizes less completely in a given time than pure selenium. To this fact the unsatisfactory action of the samples made with impure selenium is ascribed.

As insulating material soapstone was used. At first, glazed porcelain was tried, but it proved unsatisfactory on account of the difficulty of working into forms. The advantages of the talc over the porcelain are evident. It is just as efficient as an insulator, besides being much softer, and, therefore, capable of being easily machined.

Several kinds of wire were tried as electrodes, copper, nickel, platinum, German silver, and Advance wire. Again although selenides are formed during the crystallization process, due to the high temperature, the shape of the wave-length sensibility curve will not be changed, although the sensitiveness and the resistance of the cell will be affected. These points are to be verified in some later work. Copper, German silver and Advance wires have this disadvantage that, at the temperature of annealing, a film of oxide covering the wire is readily formed. This so materially increases the resistance of the cell as to make it practically useless for investigation except with very sensitive apparatus. Nickel wire is much less easily oxidized and proved as satisfactory as platinum wire, besides being less expensive, and was used in all except the first few cells.

The size of the sensitive surface was about 1×3 cm., except in the first few cells which were larger. The distance between the electrodes was a little less than 1 mm.

In applying the selenium to the form the following method was

¹ Phil. Mag., VII, p. 26, 1904.

² Marc, Die Physikalisch-Chemischen Eigenschaften des metallischen Selens, 1907.

adopted as being the most satisfactory. The form was heated, on a hot plate, to a temperature just above the melting point of selenium, 217° C., and then the selenium, in stick form, was rubbed over the heated surface immediately on removing from the hot plate. As is well known, with this treatment, the selenium at once changes, on solidification, to the gray metallic variety and is conducting and light sensitive. By this method smooth, thin films of selenium were obtained. However, in all cases in which the samples were tested out immediately on making, the resistance was found to be very high, of the order of 10^8 ohms, and the sensitiveness, even under intense illumination, in no case greater than 5 to 1. (By sensitiveness is meant the ratio of the resistance of the cell in the dark to that in the light.) Upon making, therefore, the cells were "annealed," the process taking place in an electric oven whose temperature could be quite accurately controlled. It is in this "annealing" process, which consists merely in keeping the cells for some time at a high temperature, or in gradually changing the temperature, that the changes which impart different characteristics to the cells take place. This will be described in greater detail in a later section since it is varied from cell to cell.

In general, all the samples received the same treatment after annealing. They were allowed to come to a temperature of 170° C. while in the oven, then removed and placed in small glass tubes which had been thoroughly cleaned and dried. They were then sealed to prevent the access of moisture and other vapors, and allowed to come to room temperature. Usually they were allowed to rest for 24 hours before being investigated, being kept in a light-tight box in the meanwhile. With these precautions, all the samples were found to be permanent, with respect to light sensitiveness, at least throughout this investigation.

At first, the method generally described for crystallizing the selenium namely, heating it for a few minutes at about 180° C., was followed. The first cell made in this way had a high sensibility but was not permanent. The next few samples were not at all satisfactory, so the method was abandoned. Instead, the cells were annealed at higher temperatures and a longer time was taken for the process. By this method samples were obtained which were quite satisfactory in respect to sensitiveness.

CHARACTERISTICS OF THE CELLS.

The cells were investigated with respect to resistance, sensitiveness, shape of wave-length sensibility curve and permanence.

Resistance.

The resistance of the cells was measured by means of a Wheatstone bridge. Since the resistance varies with the voltage impressed upon it, the same E.M.F., 16 volts, was used throughout.

Here the observations of Ries¹ in regard to the variation of resistance with annealing were verified. Thus Ries records two samples which were heated at different temperatures, and shows that the higher the temperature to which the cell was heated the lower was its resistance. His method differs from that employed in this investigation, however, in that he subjected the individual cells to a series of temperature changes, alternately heating and cooling each cell, and measuring its resistance and sensitiveness while it was at room temperature. In these experiments each cell was subjected to a high temperature but once, but the results were the same as those obtained by Ries. The following table gives some typical data.

TABLE I.

No. of Cell.	Temp. of Annealing.	Period of Annealing, Hrs.	Resistance, Ohms.
23	210–200° C.	6	233,000
22	210° C.	4	358,000
28	210° C.	5	490,000
16	180° C.	3½	1,400,000
15	190° C.	2	3,690,000

From the above table the influence of annealing on the resistance of the cells can be clearly seen, namely, that the higher the temperature of annealing and the longer the time, the lower is the resistance.

It was further found that if the cells were heated for a short time only at a high temperature and the annealing carried on to completion at a lower temperature the resistance of the cells was materially reduced. This fact is shown in Table II. Thus, cells No. 18 and 19 were given

TABLE II.

Cell.	Temp. of Annealing.	Period of Annealing, Hrs.	Resistance, Ohms.
18	210° C.	½	976,000
	180° C.	9	
19	180° C.	9	40,000,000
	210° C.	½	
20	180° C.	14	250,900
21	180° C.	14	9,500,000

¹ Ries, Das elektrische Verhalten des Kristallinischen Selens gegen Wärme und Licht, 1902.

exactly the same treatment except that cell No. 18 was given a preliminary heating of half an hour at 210° C. The resistance of No. 18 is seen to be less than 1/40 that of No. 19. The same is true of No. 20 and 21.

The resistance of the freshly made cells was, in general, low, but increased gradually, reaching a constant value in a few weeks after making. This gradual, permanent increase is no doubt due to the contraction of the selenium and its consequent tearing away from the electrodes. The resistance of the various samples ranged from 12,000 ohms to 42,000,000 ohms.

Light-Sensitiveness.

With regard to the effect of annealing on the sensitiveness of the cells not much can be said as a result of these experiments. Two cells of remarkably high sensitiveness were obtained, but this was not permanent, the sensitiveness decreasing to about 1/5 of the original value in less than one month. That phase of the subject is under investigation at the present time, nothing definite having been discovered thus far, however. The sensitiveness of the samples, with the exception of the two mentioned above, varied between 5/1 and 20/1, using a 16 c.p. light at a distance of 30 cm. as a source of illumination.

The Wave-Length Sensibility Curves.

In order to determine the wave-length sensibility curves, the same method of procedure as outlined by Brown and Sieg¹ was followed and the same apparatus was used. Three periods of exposure of the cell to light were used; .4 sec., 10 sec., and 30 sec., the time of exposure depending upon the resistance of the cell. The range, in general, was from 460 $\mu\mu$ to 800 $\mu\mu$, since at values lower than 460 $\mu\mu$ the energy of the source was not great enough to measure very accurately. The exposure always took place in the order from short to long wave-lengths, since Brown and Sieg have shown that the order of exposure does not affect the shape of the curve. The slit width and other factors were kept constant throughout the investigation.

It was found that, except in a few cases, the shape of the wave-length sensibility curve did not change, whether the intensity of the incident light were high or low, or whether the time of exposure were long or short. This is shown by the curves for cell No. 10 in Fig. 1. Here the wave-lengths are plotted as abscissæ, and the change in resistance, which is proportional to the deflection of the galvanometer, as ordinates.

¹ Loc. cit.

It is seen from Fig. 1 that the curves for cells of the type represented by No. 10 do not change in their essential characteristics when the energy of the incident light is varied by as great a factor as 50, nor when the time of exposure changes from .4 sec. to 30 sec. Whenever possible, therefore, on account of the sensitiveness of the apparatus, the exposures were made for .4 sec. Cell 17, Fig. 1, represents the type in which a change in the energy of the incident light changes the shape of the curve. These are the typical curves obtained by other observers for the Giltay type of cells.

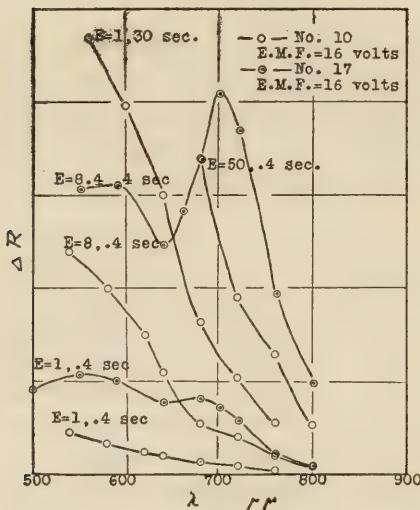


Fig. 1.

A wide variety of types of sensibility curves resulted, maxima being obtained at points not previously recorded. Fig. 2 shows the location of some of the most pronounced maxima developed in this investigation. These curves are not plotted to the same scale and, hence, do not show the relative sensibility of the cells; neither do they represent all the

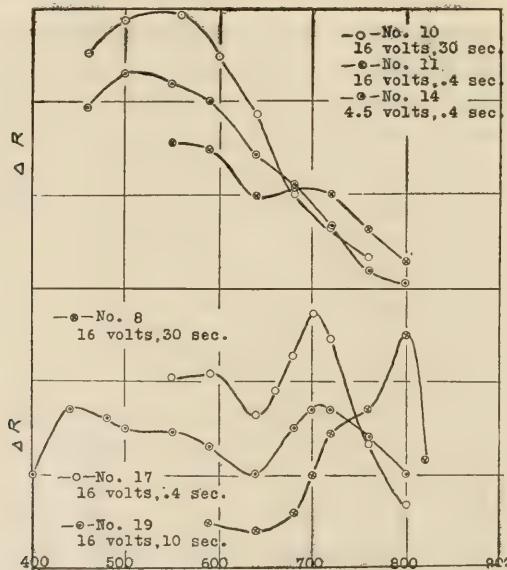


Fig. 2.

types possible to obtain. At the following wave lengths definite maxima were found: $440 \mu\mu$, $500 \mu\mu$, $550 \mu\mu$, $700 \mu\mu$, $720 \mu\mu$ and $800 \mu\mu$.

From Fig. 2 it is seen that the cells can be divided, in general, into two groups, viz., those that have their maximum sensibility at wave-lengths greater than $640 \mu\mu$, and those in which the maximum occurs at wave-lengths shorter than $640 \mu\mu$. In no case was a maximum found at $640 \mu\mu$, nor has the author been able to find one recorded at this point.

One type of cell represented by No. 19, Fig. 2, has two maxima, both of about the same magnitude and very sharply defined, one in the violet at $440 \mu\mu$, and one at $700 \mu\mu$ or $720 \mu\mu$. This type is obtained when, after applying the selenium to the form in the manner previously described, it is heated for about 10 hours at 180°C .

Fig. 3 shows the effect of a variation in the temperature of annealing on the shape of the wave-length sensibility curve. This set of curves is typical of a large number obtained when the conditions of temperatures were the same as those indicated here.

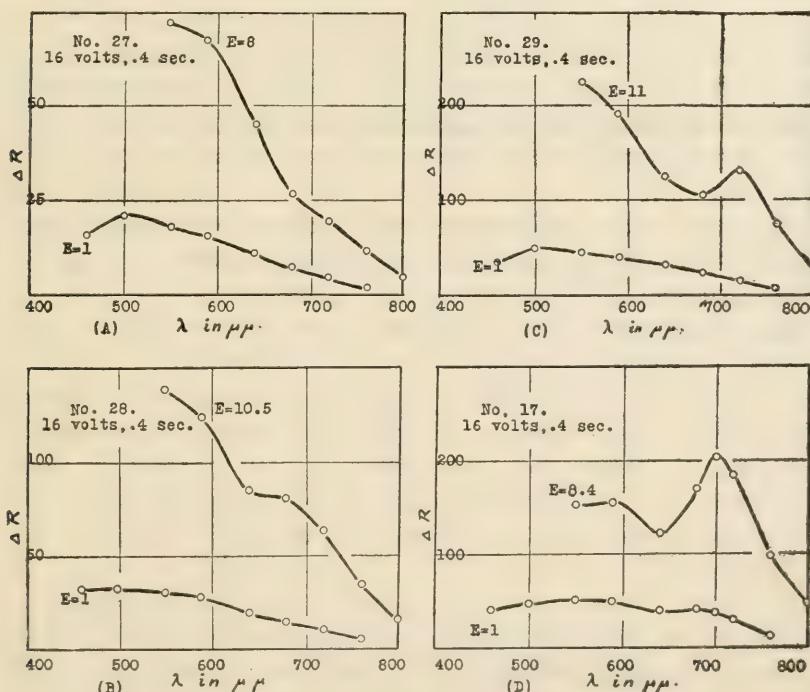


Fig. 3.

(A), Fig. 3, represents the type of curve obtained, when the cell, immediately after making, is subjected to a temperature of 210°C . for

some time, in this case, 4 hours. This type shows a maximum about $500 \mu\mu$, and very little sensitiveness above $640 \mu\mu$.

(B), Fig. 3, represents the type resulting when the cell on making is subjected for a short time to a temperature of 210° C., in this case 1 hour, the temperature then allowed to fall to 200° C. and kept constant at this point for 4 hours. Here is seen a change in the shape of the curve and a hint of a maximum in the red.

(C), Fig. 3, represents the type obtained when the cell is heated at 210° C. for 30 min., the temperature allowed to fall to 190° C. and kept constant there for 6 hours.

(D), Fig. 3, represents the type resulting when the cell was heated for 30 min. at 210° C. and then at an average temperature of 170° C.

The control of the maximum in the red end of the spectrum is clearly shown by the curves in Fig. 3. As the temperature of annealing becomes lower, the maximum in the red becomes, relative to that in the blue, gradually higher, until in the type (D) it exceeds that in the blue.

In each case described above the preliminary heating at 210° C. was given in order to lower the resistance of the cell, as was seen to be the case earlier in this paper. This was done in order to increase the accuracy of the measurements, for the apparatus for obtaining the curves is more sensitive and, hence, more accurate, the lower the resistance of the cell measured.

The most obvious explanation of the variation found in the different types of cells, in the light of recent work on selenium, rests on the probable difference in the crystals composing the various types. As we have seen, a rough classification into two general types can be made, those most sensitive to red light and those most sensitive to blue. Recently Professor Brown¹ has succeeded in producing several new forms of selenium crystals of the gray metallic variety by sublimation. A cell made by depositing one variety of these on a form was found to have a maximum at $780 \mu\mu$. It is not improbable that the maximum sensitiveness of a cell composed of crystals of another variety should lie in the blue end of the spectrum.

In some recent investigations, the results of which have not yet been published, Drs. Brown and Sieg have found the maximum sensitiveness of a single crystal of a certain variety to be in the red end of the spectrum. In another variety two maxima were found, one in the long wave-length and one in the ultra-violet. Moreover, the location of the maximum is found to be dependent upon such factors as the angle of incidence and the intensity of the exciting light, the face of the crystal illuminated, etc.

¹ PHYS. REV., Series 2, IV, p. 85, 1914.

The explanation of the different types of cells on this basis, then, is simple. A cell, such as is represented by (*A*), Fig. 3, may be assumed to contain crystals which are sensitive to a great extent only to blue light, and few or none at all of those sensitive to red light. In other words, the temperature at which this type is annealed is too high to allow the formation of crystals sensitive to red light. Another type, (*C*), for instance, might be thought of as containing a mixture of the two varieties, the amount of the "red" crystals present not being sufficient to overcome the effect of the "blue" crystals. The type represented by cell No. 19, Fig. 2, can be explained on the same basis, *i. e.*, composed of crystals having maxima both in the red and in the ultra violet, and in which the point of maximum sensibility has been shifted towards the visible spectrum, due to a variation in some one or more of the conditions governing the formation of the crystals. The occurrence of maxima separated by only a few wave-lengths can be explained by assuming a difference in the orientation of the crystals in the various cells, so that in different cells different crystal faces are exposed. Or, the light transmitted through the surface layer may suffer changes, by reflection from the crystal surfaces, causing an effect different from that it would have were it direct. This effect might be manifested by a shift in the maximum.

If the above conclusions are correct, the problem of the explanation of the light sensitiveness of selenium reduces to an explanation of the changes taking place in the single crystal under the influence of light and other agencies.

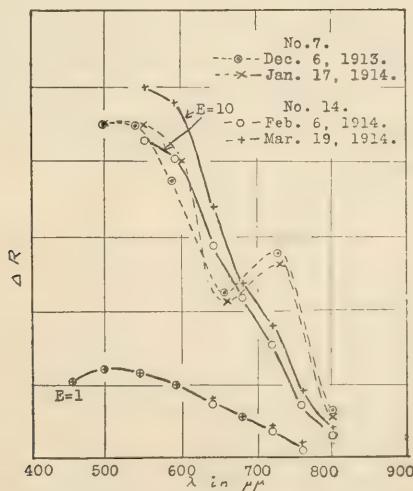


Fig. 4.

Permanence of the Characteristics.

It is evident that no definite statement as to the permanence of the characteristics of the various types can be made at the present time, since the time elapsed is hardly long enough to warrant that. Fig. 4 shows the characteristic curves of two cells taken at different time intervals, under as nearly the same conditions as possible. It is seen that they are the same in the essentials, the slight differences can be attributed to experimental errors.

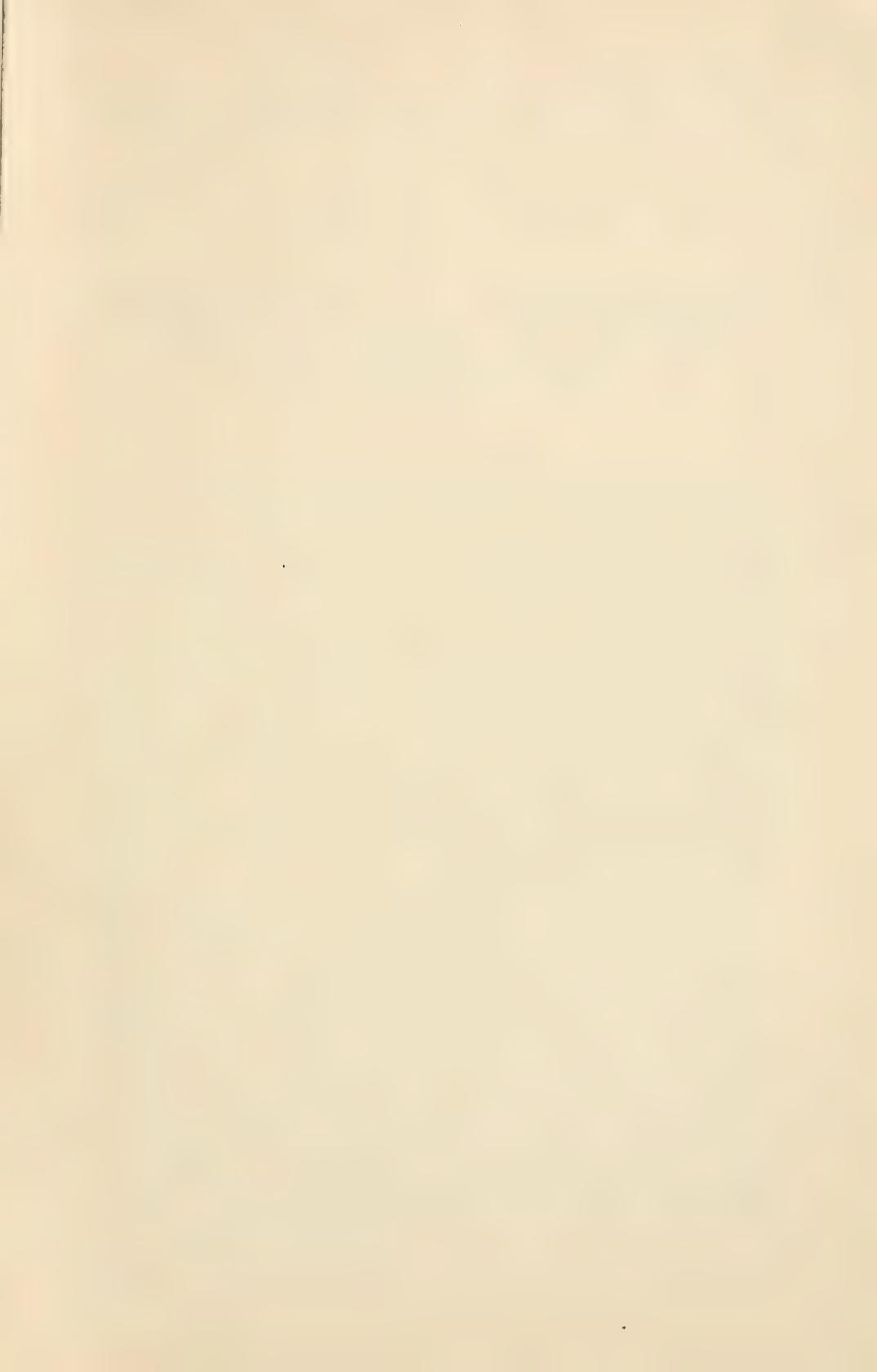
SUMMARY.

In this paper has been shown:

1. That the resistance of selenium cells depends to a great degree upon the treatment to which they have been subjected while annealing them.
2. That the location of the maximum in the wave-length sensibility curve can be controlled by a variation in the conditions under which the selenium in the cell is crystallized. It was shown that the temperature variations play the most important part.
3. That the various types of cells produced in this investigation can be explained by assuming the presence of various kinds of crystals, or different positions of the same kind of crystals in the cells. The temperature at which one kind is formed may not be favorable for the formation of another kind, hence, the production of the different types of cells.

In conclusion, I wish to acknowledge my indebtedness to the staff of the department of physics for their interest in the problem, especially to Professors Brown and Sieg for the use of their apparatus, and for their many helpful suggestions, and to Messrs. Scott Walker and Paul Helmick who so ably assisted me in much of the experimental work.

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WAVE-LENGTH-SENSIBILITY CURVES OF CERTAIN CRYSTALS OF METALLIC SELENIUM; AND A PARTIAL EXPLANATION OF THE COMPLEXITY OF LIGHT-ACTION IN SELENIUM CELLS.

By L. P. SIEG AND F. C. BROWN.

IN a recent paper¹ it was shown that there was no apparent characteristic wave-length-sensibility curve for light-sensitive selenium, except when that selenium was made light-sensitive under very definite physical conditions. Some of these conditions have recently been worked out and published by Dieterich². The conclusion seemed advisable if not necessary that the selenium in the selenium cell must be made up of a varying crystal structure, and that in some way the varying characteristics could be explained in terms of the individual crystal units composing the selenium. The recent production by one of us of several crystals of large size³ has made it possible to obtain further evidence as to the manner in which the individual crystals might explain the variations in mass selenium. In the present work we have studied the wave-length-sensibility curves of a number of crystal forms and have already obtained curves which can explain most of the variations found in selenium. As predicted in our former paper we have found these crystals to have directive axes in the property of light-action as well as in the property of light transmission and crystal structure.

The method for obtaining the wave-length-sensibility curves was in the main the same as that described in our former papers. However for adjusting to equal energy throughout the spectrum the procedure was altered to permit of more rapid working. An aluminium sector disc was calibrated in use with a given Nernst glower, in such a manner that a particular setting of the sector for a corresponding wave-length always allowed the same energy to fall on the thermopile or the crystal as desired. For comparative work with different crystals this method was very satisfactory indeed. From time to time the energy values were checked just prior to each light exposure on the crystal, and as these results

¹ PHYS. REV., N.S., Vol. 4, p. 48, 1914.

² PHYS. REV., N.S., Vol. 4, p. 467, 1914.

³ PHYS. REV., N.S., Vol. 4, p. 85, 1914.

checked and because crystals of like character always gave the same sensibility curves under the same conditions, it was certain that no important errors accrued from the method used.

Some of the crystals were not sensitive enough to be used with short periods of illumination. For this reason

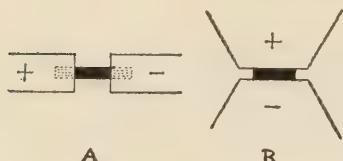


Fig. 1.

all crystals were compared for illumination of 30 seconds' duration. Just what differences exist because of varying periods should be investigated in connection with the rates of change as designated in previous papers.

The light-sensibility of the crystal was obtained when it was placed between electrodes of the same material as diagrammed in Fig. 1. Both silver and brass electrodes were used at different times, but thus far there does not appear to be any importance to be attached to the material or the structure of the electrodes. In one apparatus, designated *A*, the crystal was pressed against a glass plate by two silver electrodes acting on the ends of the crystal. The illumination could thus be applied to either the front or the back side of crystal, as well as to the edges of the crystal. In the apparatus, *B*, the entire crystal was clamped between brass electrodes. It is to be noted that in the apparatus *A* the light acts directly on the part of the selenium that is not under pressure by the electrodes and that conversely the crystal when placed in apparatus *B* was under pressure at the place of illumination. Further on will be mentioned slight modifications of these methods of clamping. It will appear that the advantages of any one method will depend largely on the shape of the crystal to be used and the crystal face to be illuminated.

COMPARATIVE RESULTS WITH INDIVIDUAL CRYSTALS AND WITH SELENIUM CELLS.

At different times we have shown that light-sensitive selenium is not a simple substance but a complex mechanism and we have taken the view that the complexities arise from more or less elementary constituents. This requires that the atom of selenium can not be the sole unit in the mechanism acted upon. The information that we have thus far is very strong evidence that the variation of the properties of light-sensitive selenium is inherent in the crystals that compose it, that these crystals by virtue of their form, position and location determine the properties of the selenium mass. The reader will we believe become at once sympathetic to this view by a casual observance of the wave-length-sensibility curves in Figs. 2a and 2b. Fig. 2a is taken from our former

paper¹ and represents the characteristic curves of various varieties of light-sensitive selenium as found in selenium cells. Fig. 2b represents the characteristic sensibility curves of individual crystals, which differ in crystal form or differ as to the direction of the crystallographic axis with regard to the direction of illumination. We do not claim to have exhausted the list of crystals or possible curves that might be obtained

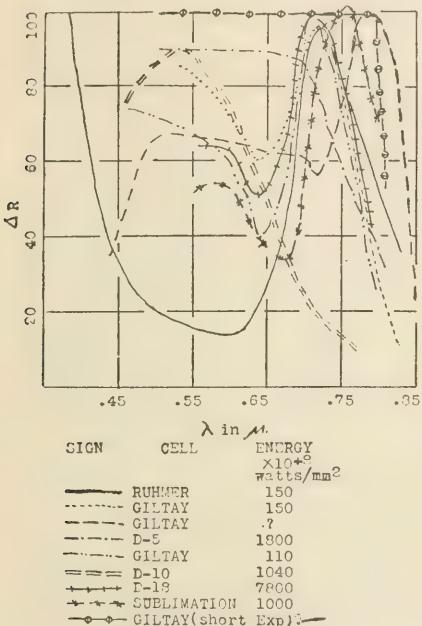


Fig. 2a.

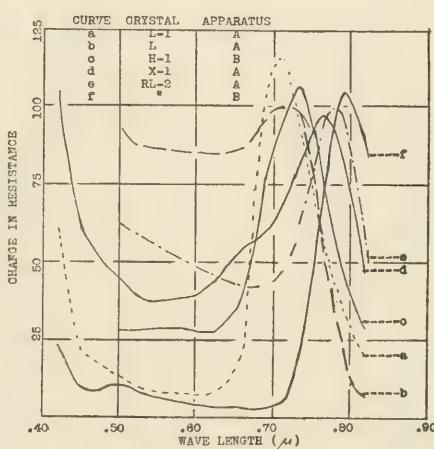


Fig. 2b.

with individual crystals. In fact some crystals already discovered have not been investigated because of their insufficiently large size. However the resemblance between the two sets is striking indeed. Both show some curves with a maximum in the ultra-violet, and both show the same range of the maximum in the extreme red. The only lack of agreement is in the fact that we have not yet discovered that crystal which has a distinct maximum in the region of $.55 \mu$, such as found in the typical Dieterich cell. And along with this fact it must be noted that we have examined no crystal which in any position showed a diminishing sensibility at the blue end of the spectrum. In making these comparisons we have made no allowance for the enormous difference in the reflecting power of the selenium in selenium cell from that of the crystal. The former absorbs about 98 per cent. of the light in all parts of the spectrum, while the

¹ Loc. cit.

latter probably does not absorb more than 60 to 70 per cent. of the incident light. What may be the consequences of this difference is not certain. It will of course be advisable to measure the absorption constant of the crystals.¹ In as much as the selenium in mass does not show a very great selective absorption and since the shifting of the red maximum is almost identical with the selenium crystals and the selenium mass, it is not expected that the crystals will show much of a variation in reflecting power in this region.

In what ways the crystals give rise to varying sensibility curves will be taken up in the remainder of the paper.

EACH CRYSTALLINE FORM HAS A DISTINCTIVE CHARACTERISTIC CURVE.

Before asserting that each crystalline form of selenium has characteristic photo-electrical properties, it is advisable to know that the character of the curve is not altered by other physical conditions which might vary in the experiments. For example it was determined that the direction of current flow did not alter the sensibility curves when the illumination was on the same part of the crystal. Since it had been shown by one of us² that the resistance might vary by a factor of several hundred depending on the pressure on the crystal, there was considerable doubt as to whether the pressure might control the character of the sensibility curves. In fact we mentioned in one of our former papers that a part of the variations in the selenium cells might be accounted for by variations in the pressure on the selenium as it was placed on the cell form. We therefore placed an acicular hexagonal crystal between the electrodes of apparatus *B* and mapped out the sensibility curves when the pressures were of such a magnitude that the conductivity increased by a factor of 50 to 1. The intensity of illumination and other physical conditions were unchanged. The results of the investigation are shown by the two upper curves in Fig. 3. There is no evidence of any change in the position of the maximum or in the ratio of the values of the maximum to the minimum as a result of the change in pressure.

Since Pfund and ourselves had observed an ironing out of the maximum in certain selenium cells by diminished illumination it was thought advisable to see if the sensibility curves underwent any change when the intensity of illumination was varied. We used the same crystal and apparatus just mentioned above. These comparison curves are also

¹ Recently a preliminary test was made to determine the reflecting power of these crystals throughout the spectrum. This was found to be practically constant, and probably between 30 and 40 per cent, thus agreeing with the values of Foersterling and Freédericksz (Amer. d. Phys. 43, 1227, 1914) for metallic and amorphous selenium mirrors.

² PHYS. REV., N.S., Vol. 4, p. 93; 1914.

shown in Fig. 3. Again there is no apparent change in the curves due to varying intensity. This result is particularly important at this point because it has not been determined if there is a variation of the reflection coefficient in different crystals or along different axes of the same crystal. If there is such a selective variation we have no means of knowing just what is the relative amounts of energy absorbed when we can measure only the incident energy. Unless the selective variation is of some magnitude, we can be reasonably certain that the amount of light absorbed by the crystal does not concern the character of the sensibility curve. Of course electrical theory requires that the reflection constant should vary with the conductivity of the material. But since the resistance of these crystals is so large, it is believed that the reflection due to the free or conducting electrons is small compared to the reflection by the charges in the bound atomic structure. The values of the intensity in Fig. 3 are for the incident energy. The values of the absorbed energy must be many times smaller, but even if the absorbed energy does vary by a factor of fifty the ratios of the absorbed energy surely can not be enough different to make any material error in the conclusions that we have drawn, concerning the independence of light-action and the pressure effect.

It has been shown¹ for selenium cells and also for single crystals that the resistance varies greatly with the electromotive force across the selenium. It is sufficient to mention here that we could not observe any change in the sensibility-curves due to a variation of the resistance by use of varying potential differences between the electrodes.

In the formation of the crystals there were sometimes variations of 20° or 30° in the oven temperature. As nearly as could be discerned such temperature treatment did not alter the sensibility curve of a given crystal form.

Having shown that the preceding conditions did not alter the character

¹ Paper by Brown and Stebbins, PHYS. REV., 26, p. 273, 1908 and Brown, PHYS. REV., 33, p. 1, 1911, and other paper not yet published.

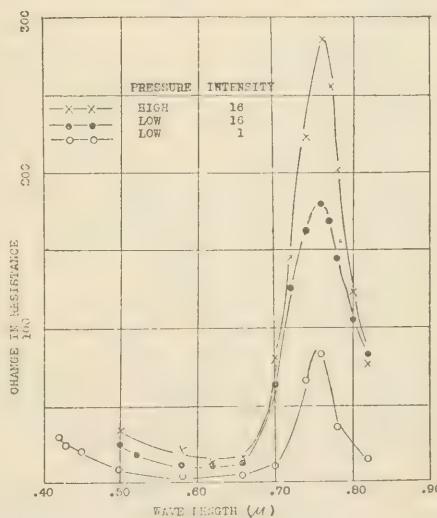


Fig. 3.

of the sensibility curves, we proceeded to investigate the variation of the sensibility curves for the different crystal forms. For this we selected three specimens which were of sufficient size for the purpose. One (*L-1*) was a lamellar crystal¹ with axes perpendicular to the edges. Its size was about $4 \times 2 \times .2$ mm. A second was of the acicular hexagonal form (*H-2*), of size about $10 \times .4 \times .4$ mm., and the third was a combination of crystals that had grown out from a central hexagonal spine. The angles and the form of this are not yet known, but the crystal is probably of the second crystal system. Crystals of the above types are shown in the above articles referred to.

The lamellar crystals were placed in apparatus *A* and illuminated perpendicular to either of the large flat surfaces. In either case the sensibility was that shown by the upper curve in Fig. 4.

The acicular crystals were placed in apparatus *B*. They were illuminated perpendicular to the axis of the crystal. It was apparently immaterial as to which of the six faces were illuminated. The curve for this type showed a sharp maximum in the same place as that for the lamellar crystal (see *H-2*, Fig. 4), but it was very much sharper and its magnitude was relatively much greater than for the lamellar crystal.

The third crystal showed a maximum at wave-length $.7 \mu$, but it was not as sharp as that of the acicular crystal (see *X-1*, Fig. 4). It should be mentioned that all the curves in this paper are drawn each to an arbitrary scale, so that the relative sensibility of each crystal can not be ascertained from the curves. In the crystals just referred to however the sensibility was of the same order of magnitude in each.

THE SAME CRYSTAL GIVES DIFFERENT CURVES WHEN ILLUMINATED ALONG DIFFERENT AXES.

Previously we have shown the crystals to be doubly refracting.² Electrical theory requires that any material having directive axes in its optical properties in this way, shall also show directive properties in any phenomena involving electro-optical interactions. Simply stated if a crystal shows electrical phenomena as a result of light acting upon the crystal as a crystal and not as an element, the electrical phenomena should vary when the illumination is along different axes. On the other hand if the light action should be on the atoms without regard to the crystal mechanism it is not conceivable how there could be any difference in the sensibility curves arising from illuminating different sides of the crystal providing the reflecting power is constant.

¹ For further information about these crystals see papers by Brown, *PHYS. REV.*, loc. cit., and by Brown and Sieg, *Phil. Mag.* (6), Vol. 28, p. 497. 1914.

² Brown, loc. cit.

Several crystals were investigated as to the conductivity change when illuminated along different axes. The best specimen was a lamellar crystal $4 \times 2 \times 0.2$ mm. The large surfaces were rectangular and approximately parallel. We were not able to determine the angles of the edge faces.

When the illumination was directed on either of the large faces as shown by the arrow, marked 1 (Fig. 5), the sensibility began to increase rapidly at wave-length $.66 \mu$ and held a broad maximum with the mean

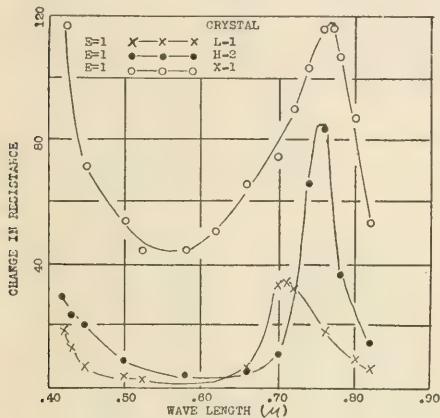


Fig. 4.

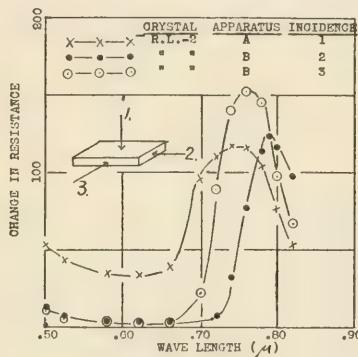


Fig. 5.

position at $.74 \mu$. At $\lambda = .80 \mu$ there was a very large sensibility. By illuminating either of the short edges of the crystal the sensibility had just started to rise at $\lambda = .74 \mu$, the position where with side illumination the maximum occurred. In this instance the maximum was very sharp and located at $.79 \mu$. In the infra red beyond wave-length $.82 \mu$ this edge of the crystal was more sensitive relatively to the minimum than was the flat surface at its maximum. When either of the longer edges was illuminated as shown by arrow 3, the maximum was at $.76 \mu$. Thus a single crystal may have its maximum shifted at least five wave-lengths by changing the side of the crystal that is illuminated. We carefully observed that the direction of current flow made no difference in these experiments.

It is altogether improbable that the variation of the selective absorption plays an important rôle in giving these different sensibility curves. If so the results are consistent with the idea that the light acts upon the crystal structure rather than upon the atoms. However this mode of explanation of the shifting of the maximum can be sidestepped perhaps if we wish, by attributing the shift toward the longer wave-lengths to transmitted action as will be explained in the last section of this paper.

THE ACTION OF POLARIZED LIGHT.

We have made some observations on the action of polarized light, the significance of which is satisfying only in a general way. The experiments were called forth after we had investigated the effect of varying the angle of incidence on a lamellar crystal. By such variations of the angle of incidence, sensibility curves were obtained for different angles as indicated in Fig. 6. For an angle of about 60° there was a decided change in the character of the curve but for angles larger or smaller the curve form was almost unchanged. It was thought that this might be about the angle of maximum polarization, and that consequently only one component of the light might enter the crystal at this angle.

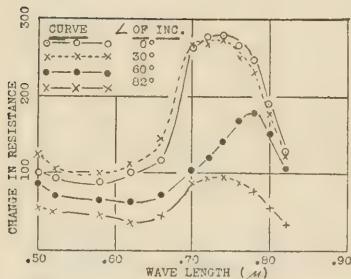


Fig. 6.

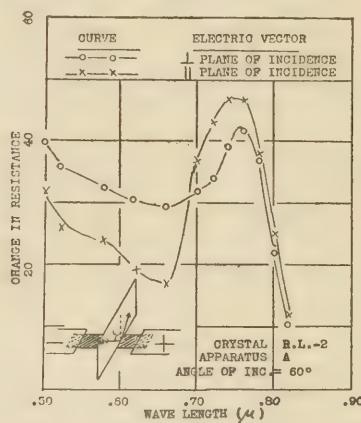


Fig. 7.

We therefore tried first light polarized in the plane of incidence and then at right angles to this plane. For all angles of incidence except 60° there was no change in the character of the sensibility curve, but at about this angle the effect of light polarized in opposite planes was quite different. When the electric vector (see Fig. 7) of the light was perpendicular to the plane of incidence the sensibility curve was much like that shown for the same angle shown in Fig. 6. But when the electric vector was parallel to the planes of incidence the maximum was relatively much broader and higher than in the previous case.

A part of the difference between the location of the maximum in Figs. 6 and 7 may have arisen from the fact that we had no accurate means of setting the angles.

We are concluding from our experiments first that our Hilger monochromator partially polarizes the light that passes through it and secondly that under certain conditions a given intensity of illumination may produce different results depending on its state of polarization.

THE DIRECT AND THE TRANSMITTED ACTION OF LIGHT.

Recently we have shown¹ that the seat of light action in selenium crystals is distributed throughout the crystal, and that light may alter the conductivity of a crystal 10 mm. or more away from the point of impingement. At that time we had not succeeded in determining whether this action could be transmitted from one crystal to another. Now we have gone further and found not only that the action of light can be transmitted from one crystal to another, but we have also mapped out the sensibility curve for such indirect action and compared it with the direct action, where the light falls on the part of the selenium between the electrodes.

We chose for this work a lamellar crystal to the middle portion of which was grown another crystal. This crystal and the apparatus *A* are shown in a very highly conventionalized way in Fig. 8. The dotted arrows show the portions that were illuminated. Wherever any or most of the light fell upon the part of the crystal carrying the current it was called direct action as indicated by the change of conductivity of the crystal. Contrarily if the light impinged on any part of the crystal

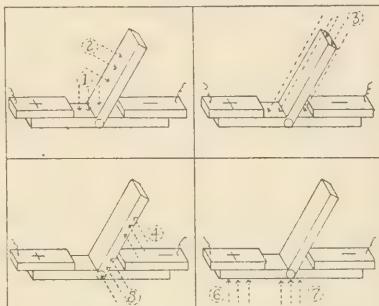


Fig. 8.

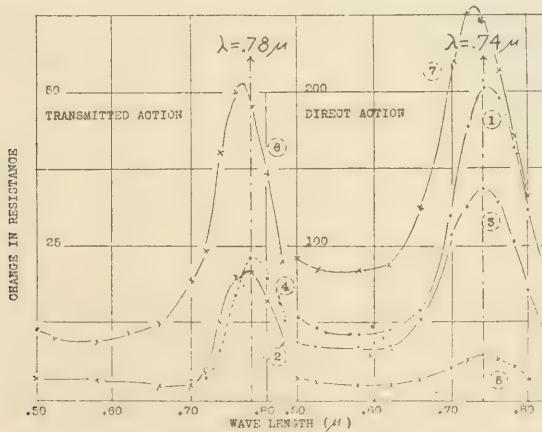


Fig. 9.

that did not carry the current, the light effect was designated as transmitted light action.

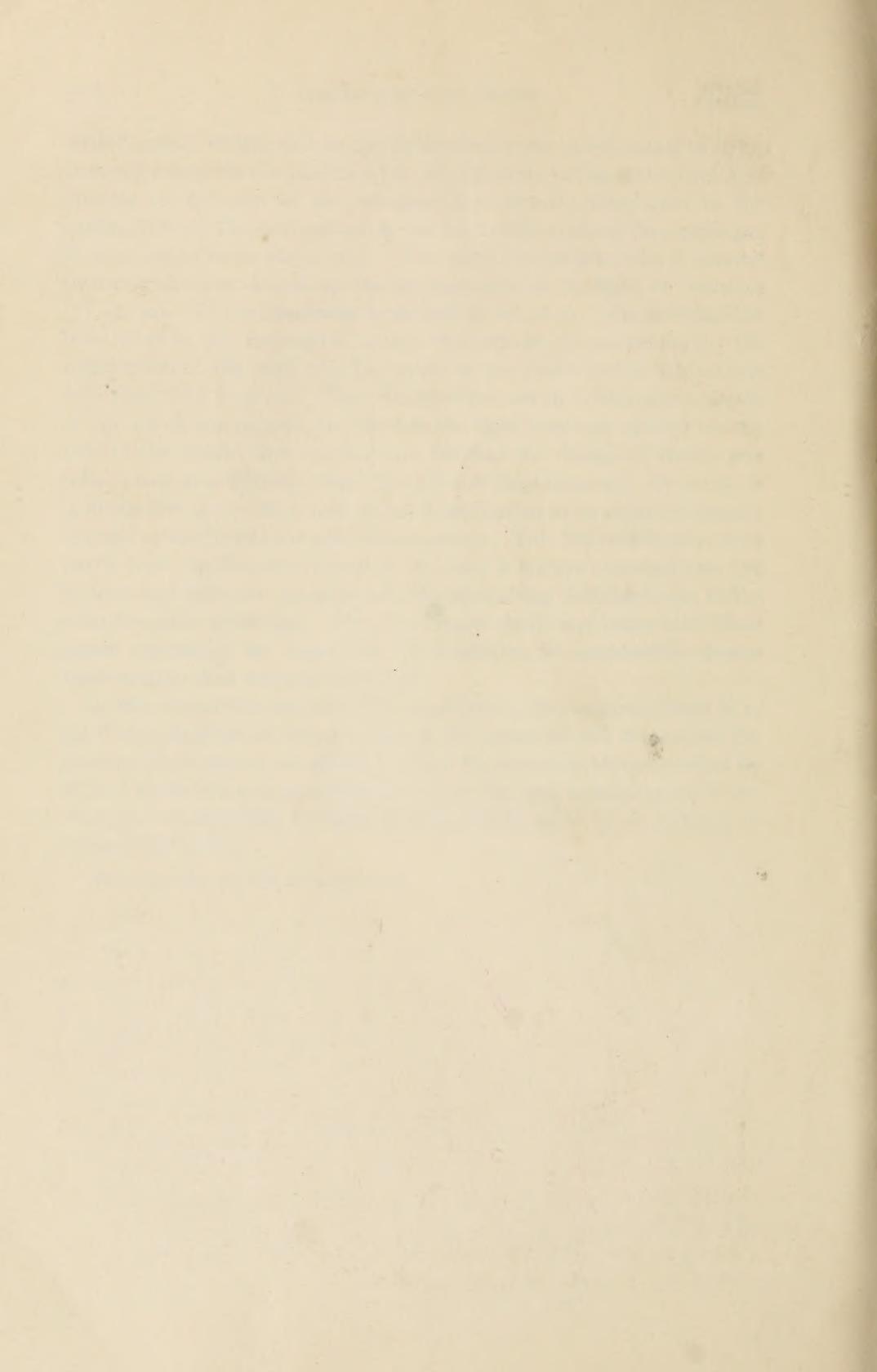
In Fig. 9 are shown the sensibility curves, on one side for the trans-

¹ Phil. Mag., Ser. 6, Vol. 28, p. 497, 1914 and PHYS. REV. N. S., Vol. 4, p. 85.

mitted action of light and on the right side for the direct action of light. It may be seen that in positions (1), (3), (5) and (7) Fig. 8 the light acts directly on the part of the selenium that directly takes part in the conductivity. The corresponding curves in Fig. 9 show the maximum in all cases to be at about $.74 \mu$. But when the conductivity is altered by transmitted action as by the impingement of the light at positions (2), (4) and (6) the maximum is shifted to $= .78 \mu$. Also it should be noted that in the transmitted action the ratio of the maximum to the minimum is of the order of 5 to 1 while in the direct action this ratio is only about half as great. Thus the position and the relative magnitude of the maximum depend on whether the light impinges directly on the part of the crystal that conducts or whether the change of conduction takes place at a distance from the point of impingement. Of course it is impossible to say what constitutes direct action or to separate entirely the two actions in the so-called direct action. This latter difficulty arises partly from the fact that a part of the light is always absorbed near the surface and does not penetrate all the conducting selenium even in the most favorable condition. Thus if we could obtain and isolate the direct action completely we might find the maximum at considerably shorter wave-lengths than we have indicated.

In this connection an interesting experiment that suggests itself is to see if the thickness of the selenium in the selenium cell determines the position of maximum sensibility. Thus the selenium blocks studied by White¹ should show a maximum far out in the red, because most of the change of conductivity by light in these blocks must be an indirect or transmitted action.

¹ Phil. Mag., Ser. VI, Vol. 27, p. 370, 1914.



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